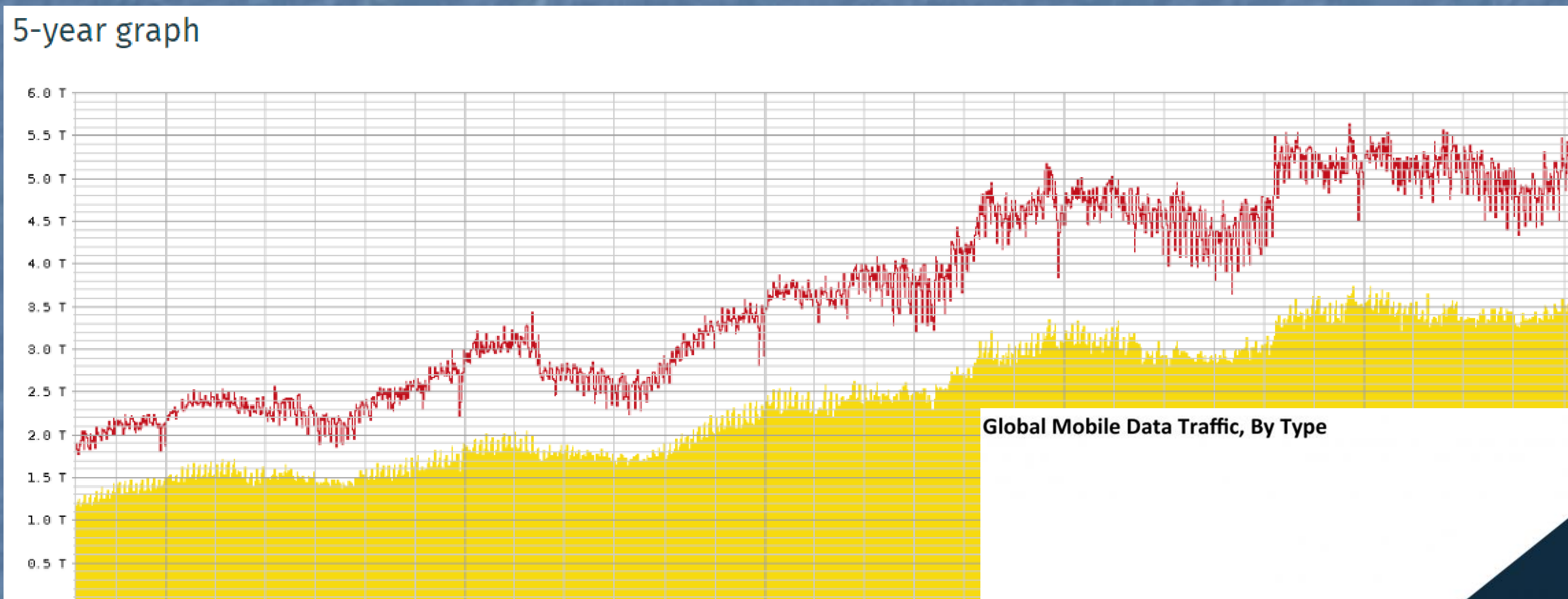
Optical Transmission Fundamentals

F. Vasey, CERN-EP-ESE

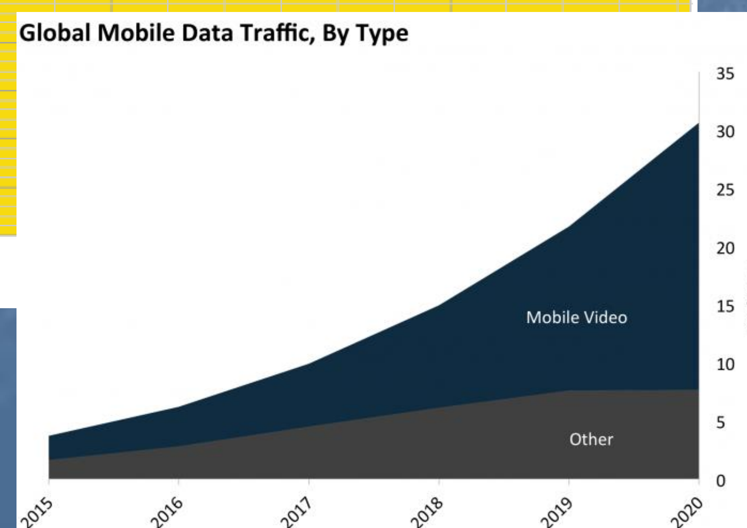
- Context
- Technology
- HEP Specifics

Context: Bandwidth Demand

Internet traffic is growing at ~Moore's law
Global interconnection bandwidth estimated to reach 8'000 Tb/s in 2021
10x increase compared to 2017

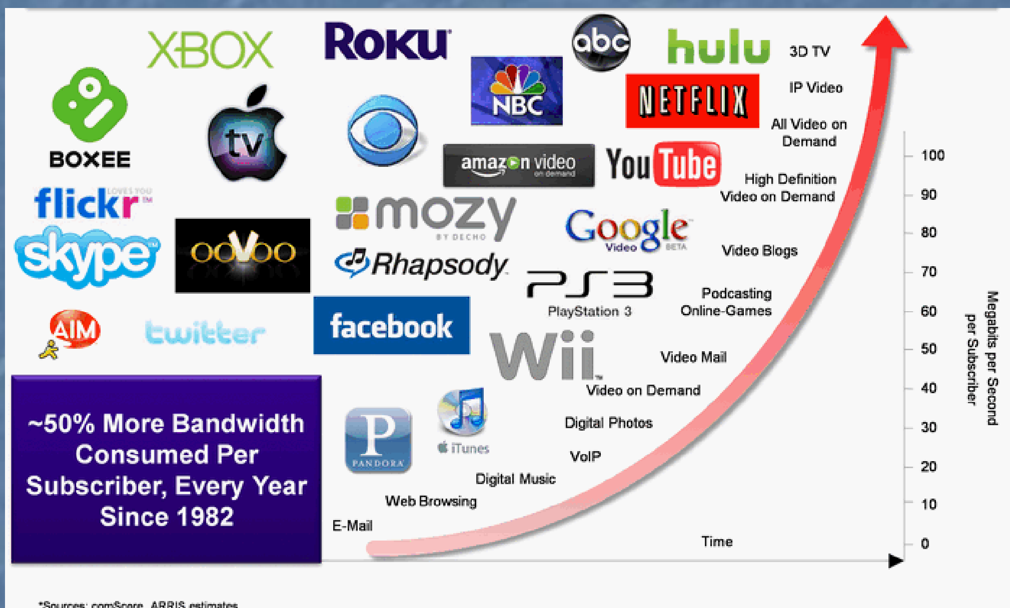


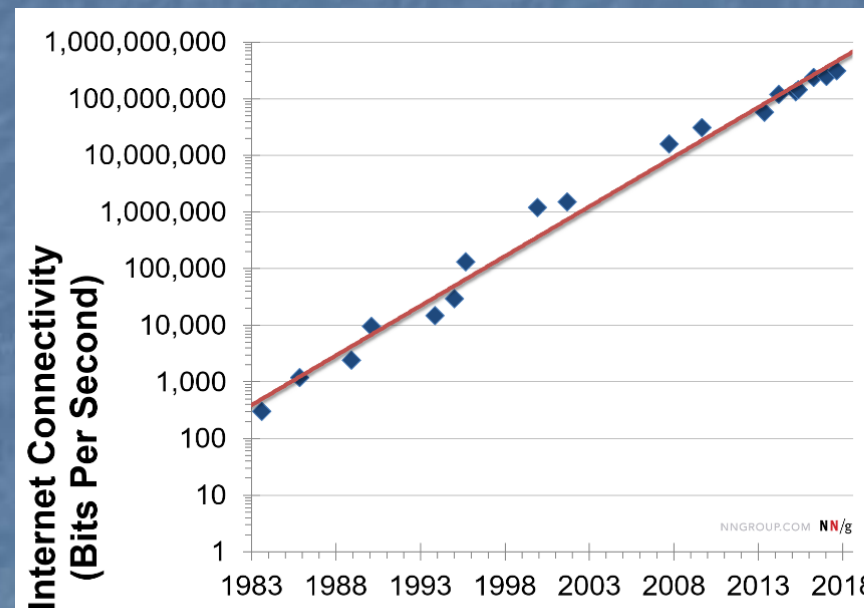
Frankfurt DE-CIX internet exchange point



Context: Bandwidth availability

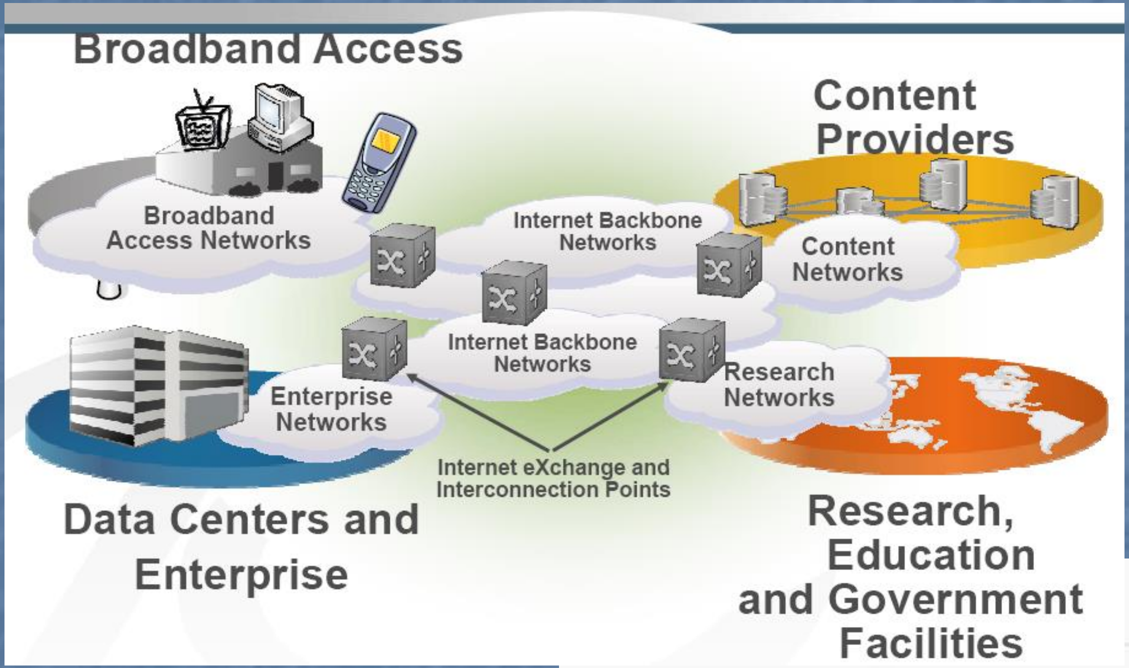
- People and objects are increasingly interconnected, ubiquitously
- Bandwidth demand is spiraling
- Access Bandwidth has grown x200’000 in 30yrs

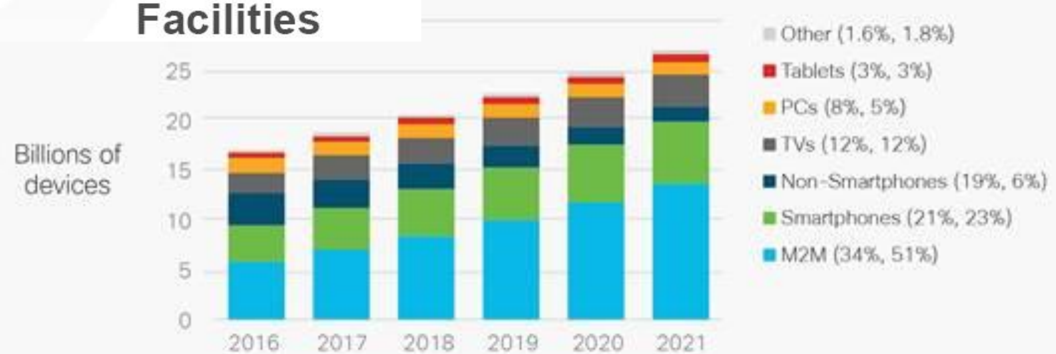




Context: … but who is feeding the network ?

In 2016:
- 1’200’000 petabytes have been exchanged worldwide
- 49 petabytes have been produced by LHC experiments





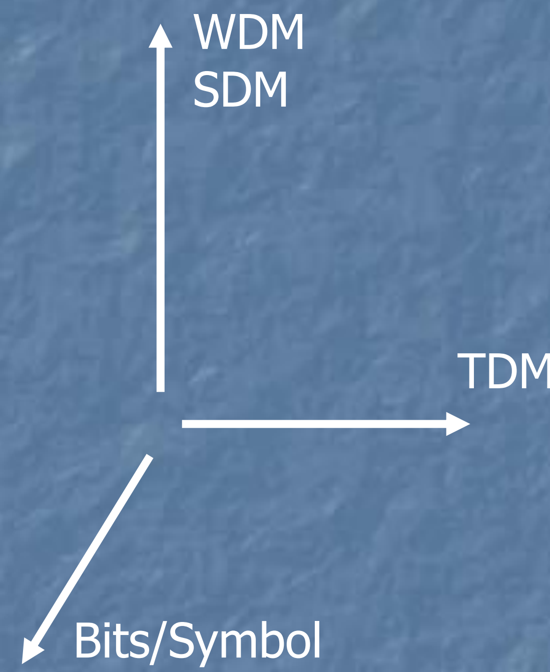
Figures (n) refer to 2016, 2021 device share.
Source: Cisco VNI Global IP Traffic Forecast, 2016–2021.

Context: Capacity is what matters

- Technology is developed at a pace that matches the needs for capacity in the networks

- Developers of electronics for physics experiments surf this wave but don't drive it

- A good understanding of the datacom environment and its evolution is thus essential to assess the potentials of optoelectronics and its future benefits



Technology

- Context
- Technology
  - Networks
  - Hardware Toolbox
  - Modulation Formats
  - Capacity
  - Standards
- HEP Specifics

Technology: Networks

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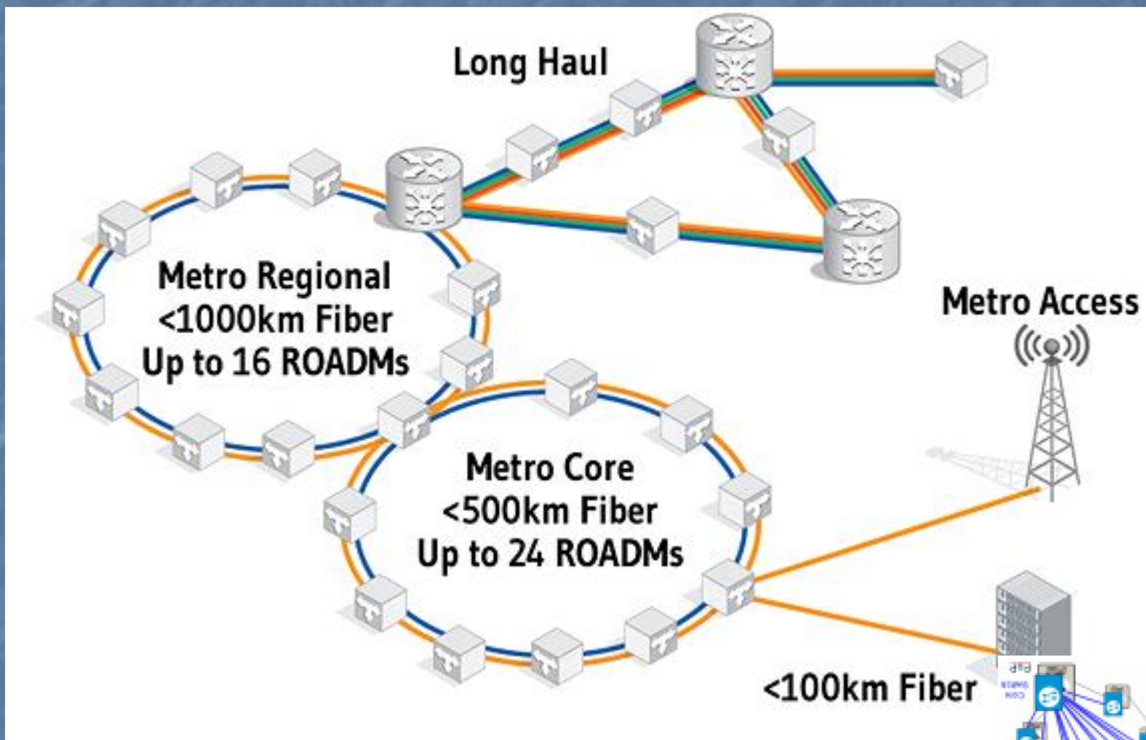
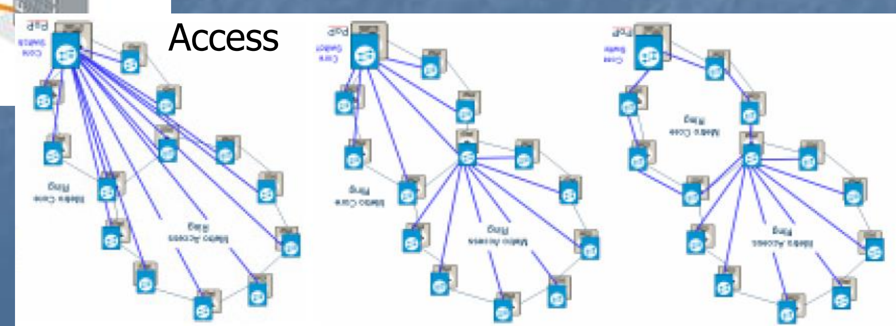
Core, Regional-Metro and Access Networks

- Different technologies are developed for the different network types
- But network specificities tend to fade
- Technologies tend to migrate from one type to the other



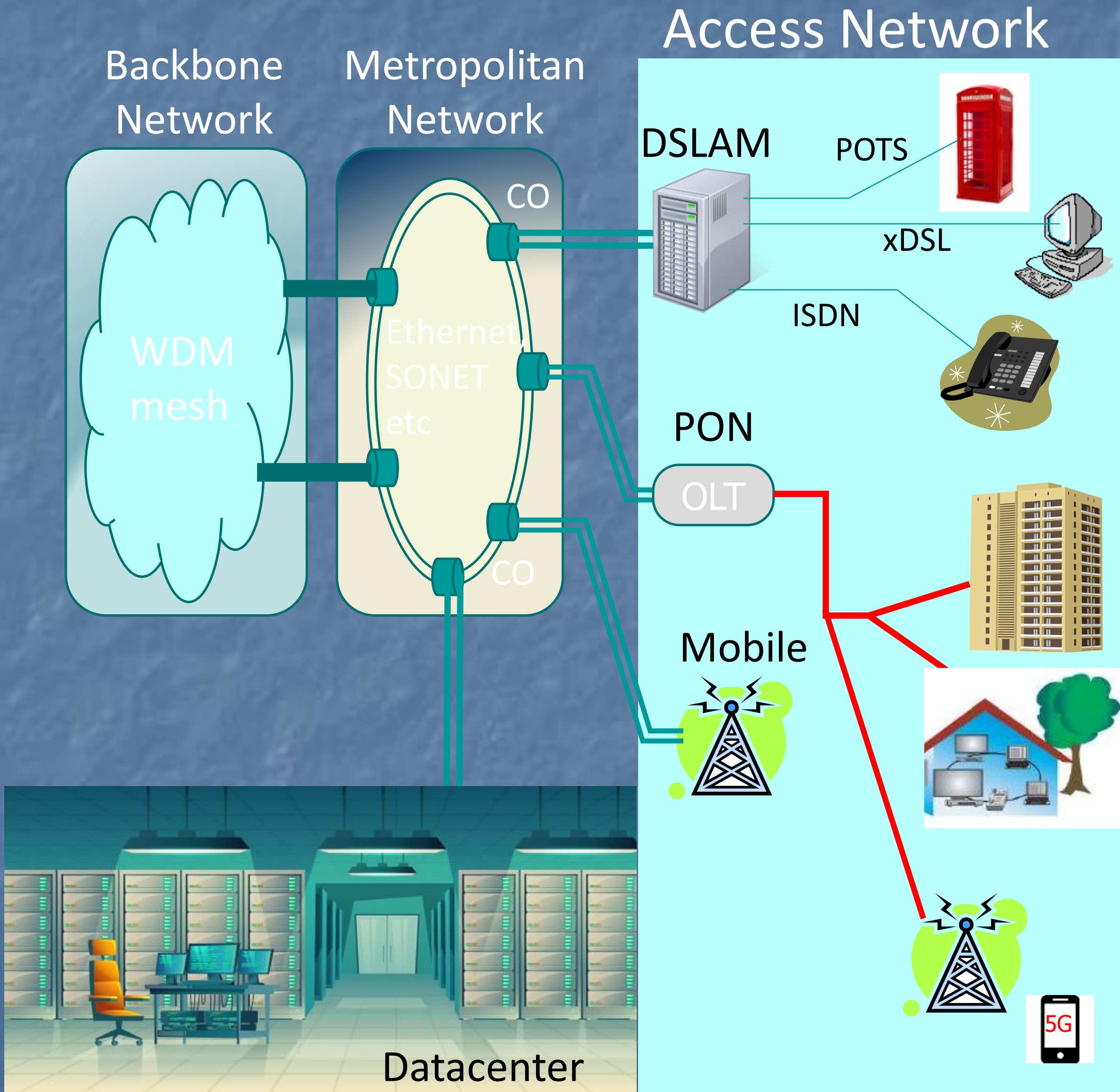


Core Network

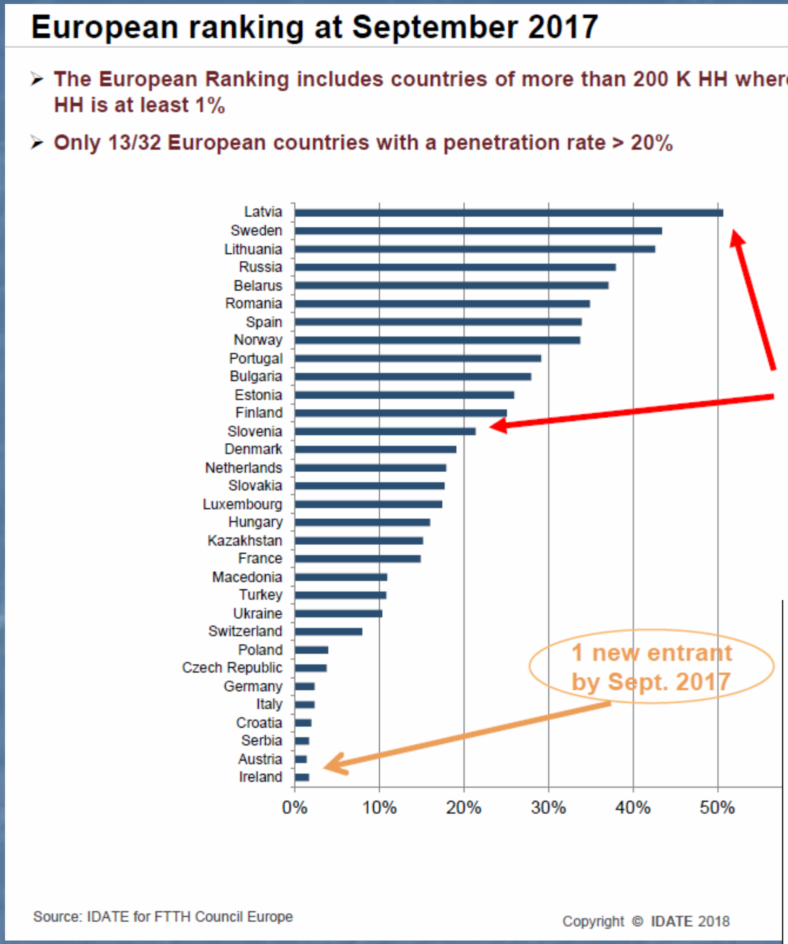
- 100 - 400Gb/s
- Fully proprietary technology
- WDM: Up to 80 wavelengths per fibre (50/100GHz spacing)
- EDFA every ~100km
- Dispersion compensation
- Forward Error Correction
- Performance driven

Access Network

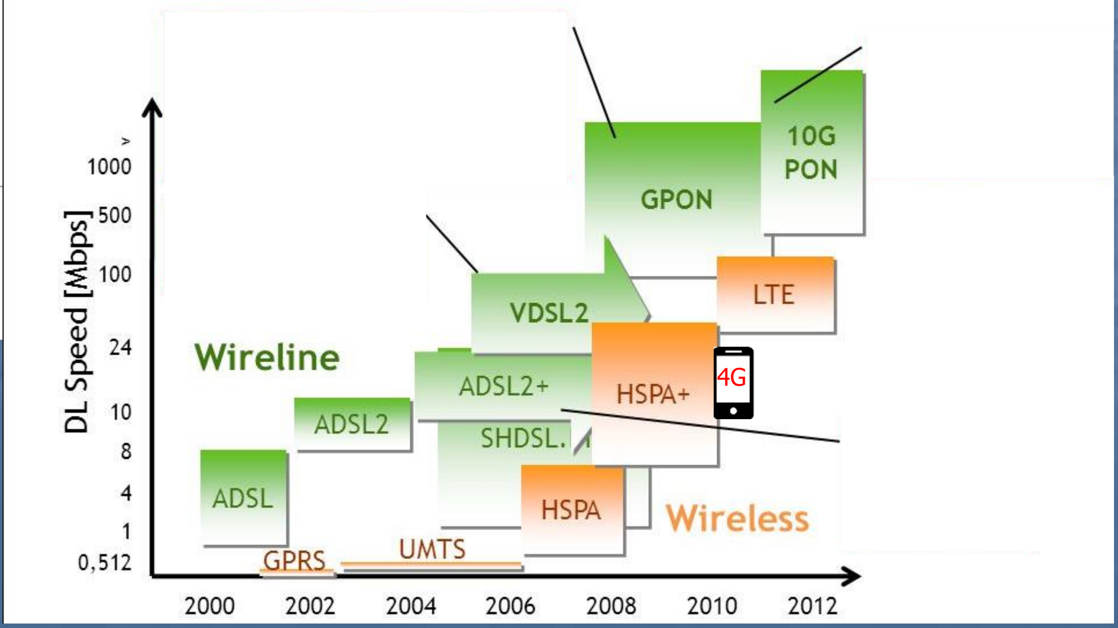
- 10-100Gb/s
- Standardized technology
  - ISDN
  - xDSL
  - Ethernet
  - GPRS, Edge, 3G, 4G
  - PONs…
- No wavelength multiplexing (so far)
- Cost/regulation sensitive



Access Network: Fiber penetration



- Penetration still far from 50%



Summary: of direct interest to DAQ systems developers:

- 10-100Gb/s
- Standardized technology
  - ISDN
  - xDSL
  - Ethernet
  - GPRS, Edge, 3G, 4G
  - PONs…
- No wavelength multiplexing (so far)
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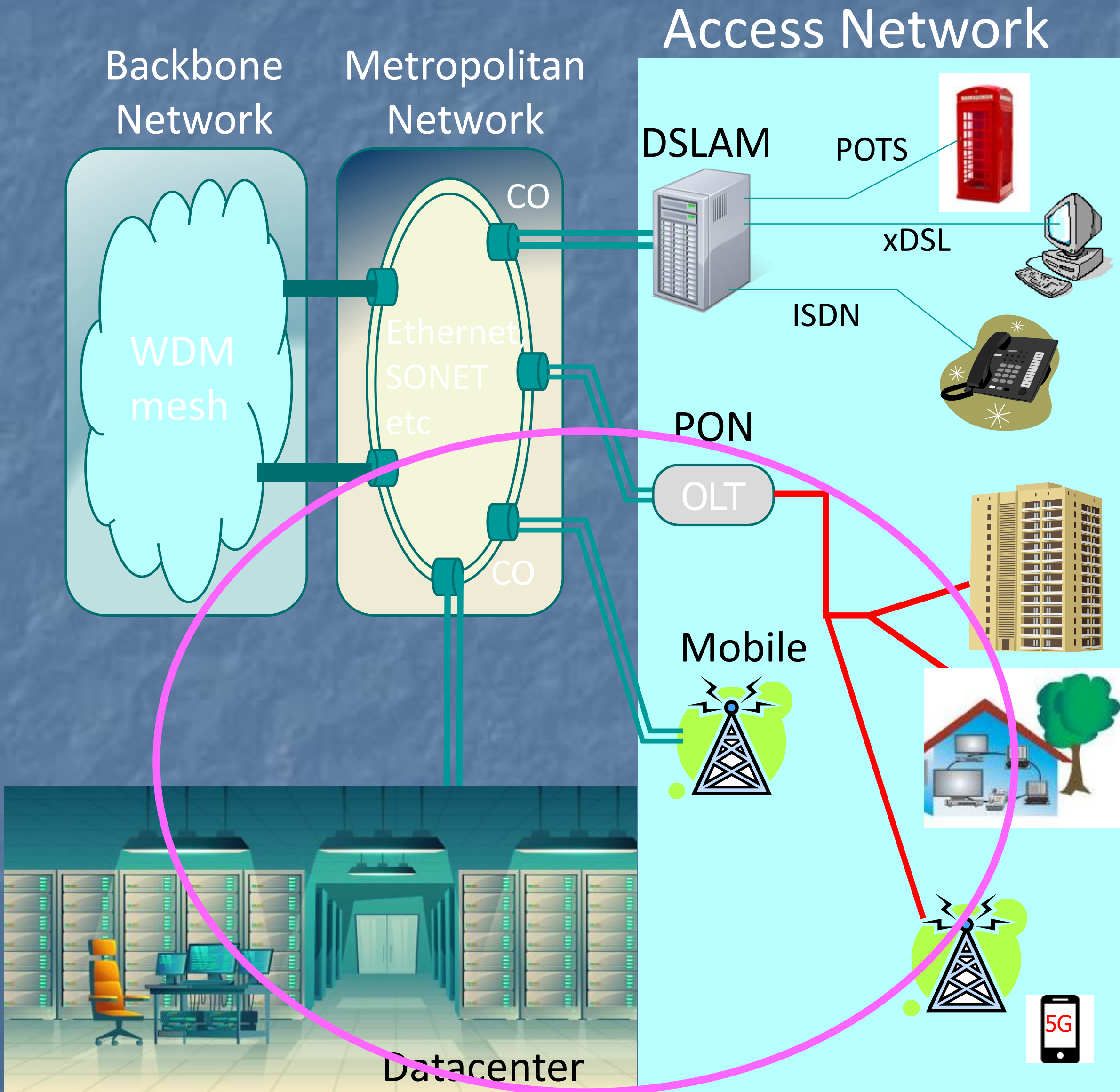

Technology

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  - Hardware Toolbox
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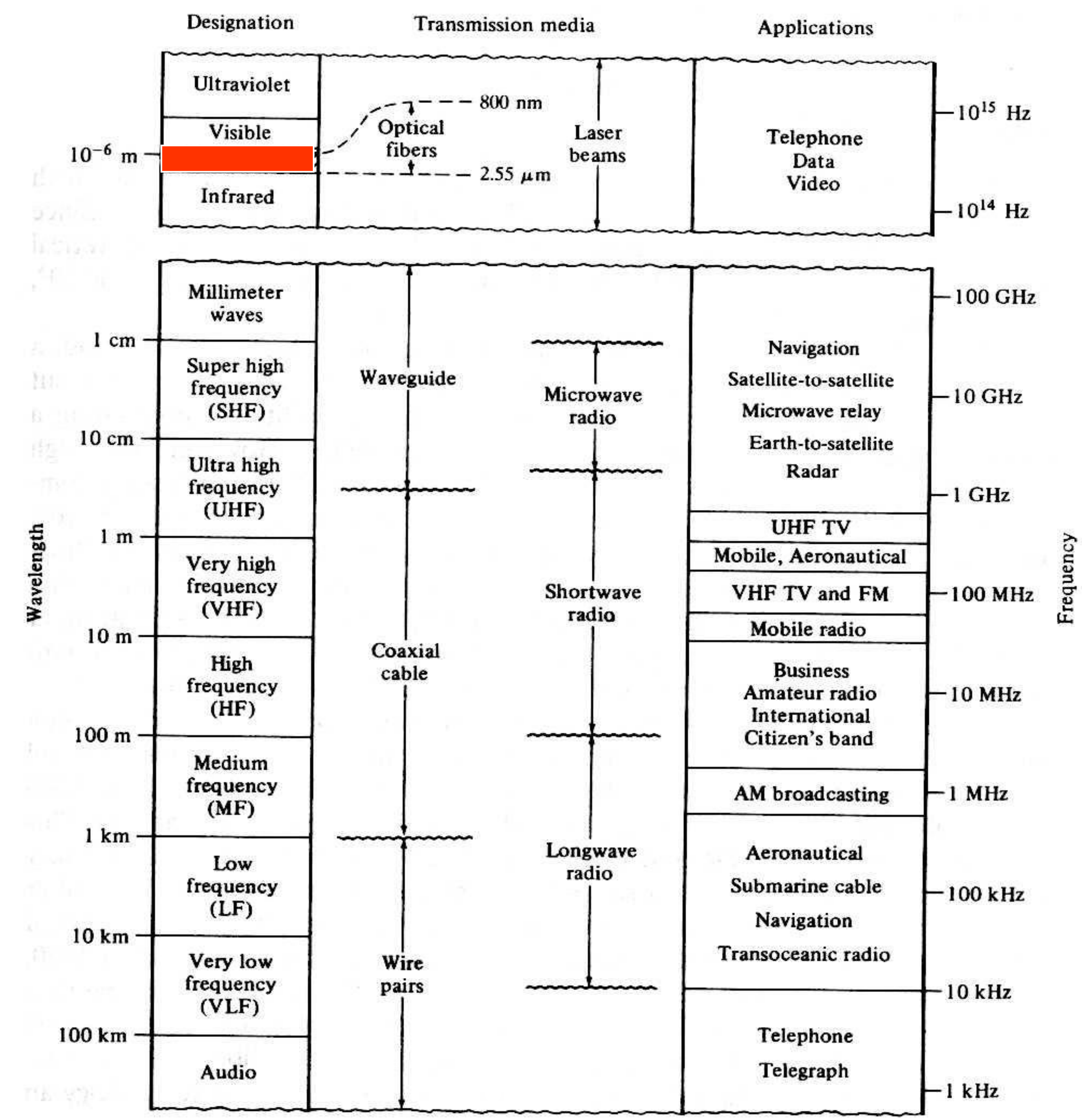
EM Spectrum

- EM spectrum usage:
- 1840s Telegraph
- 1880s Telephone
- 1890s Radio
- 1940s Microwaves
- 1950s bipolar transistors
- 1960s Lasers
- 1970s Optical fibres
- 1990s Er-doped fibre

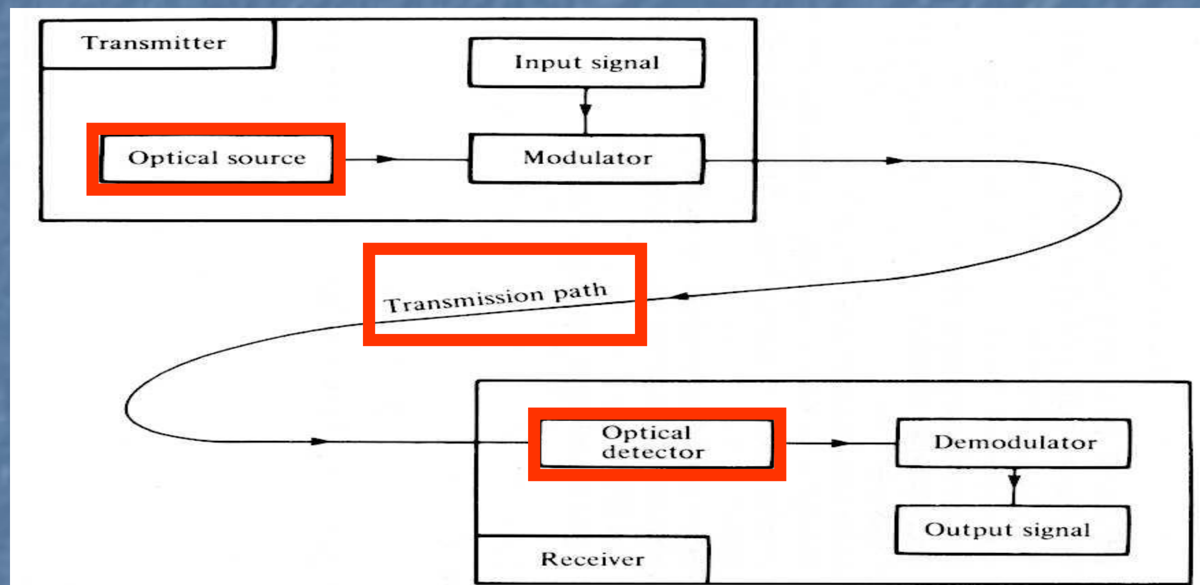


Data Transmission Model

Emission

Refraction
Attenuation
Dispersion

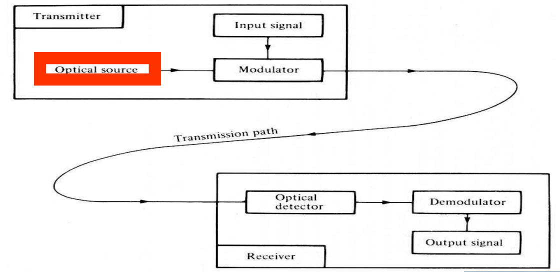
Absorption

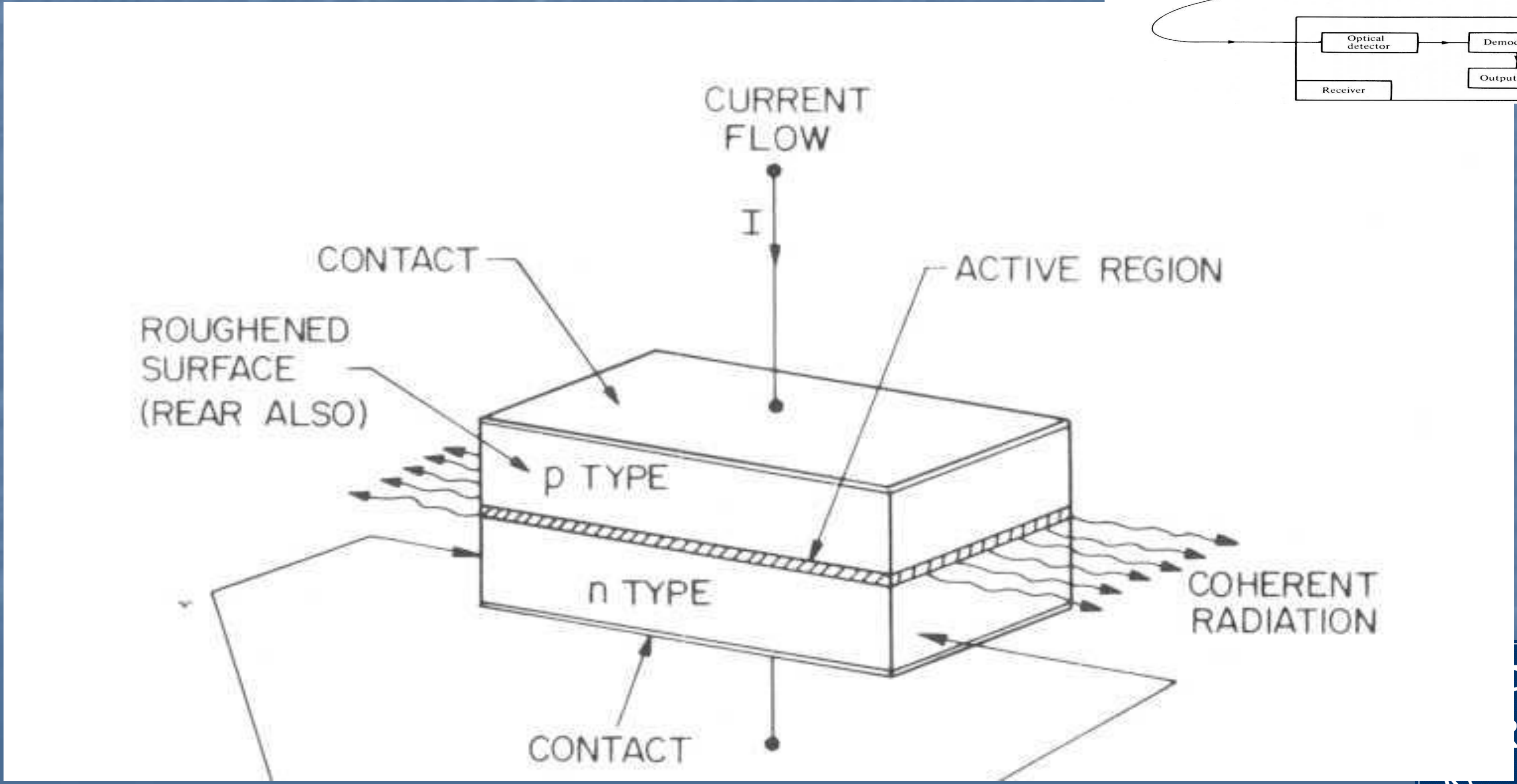


- Optical communication systems are not new
- Greek fire chains with relay stations existed 1000years BC
- Missing for a long time was the perfect match of bandwidth, distance and availability

1. Emission in semiconductor cristal

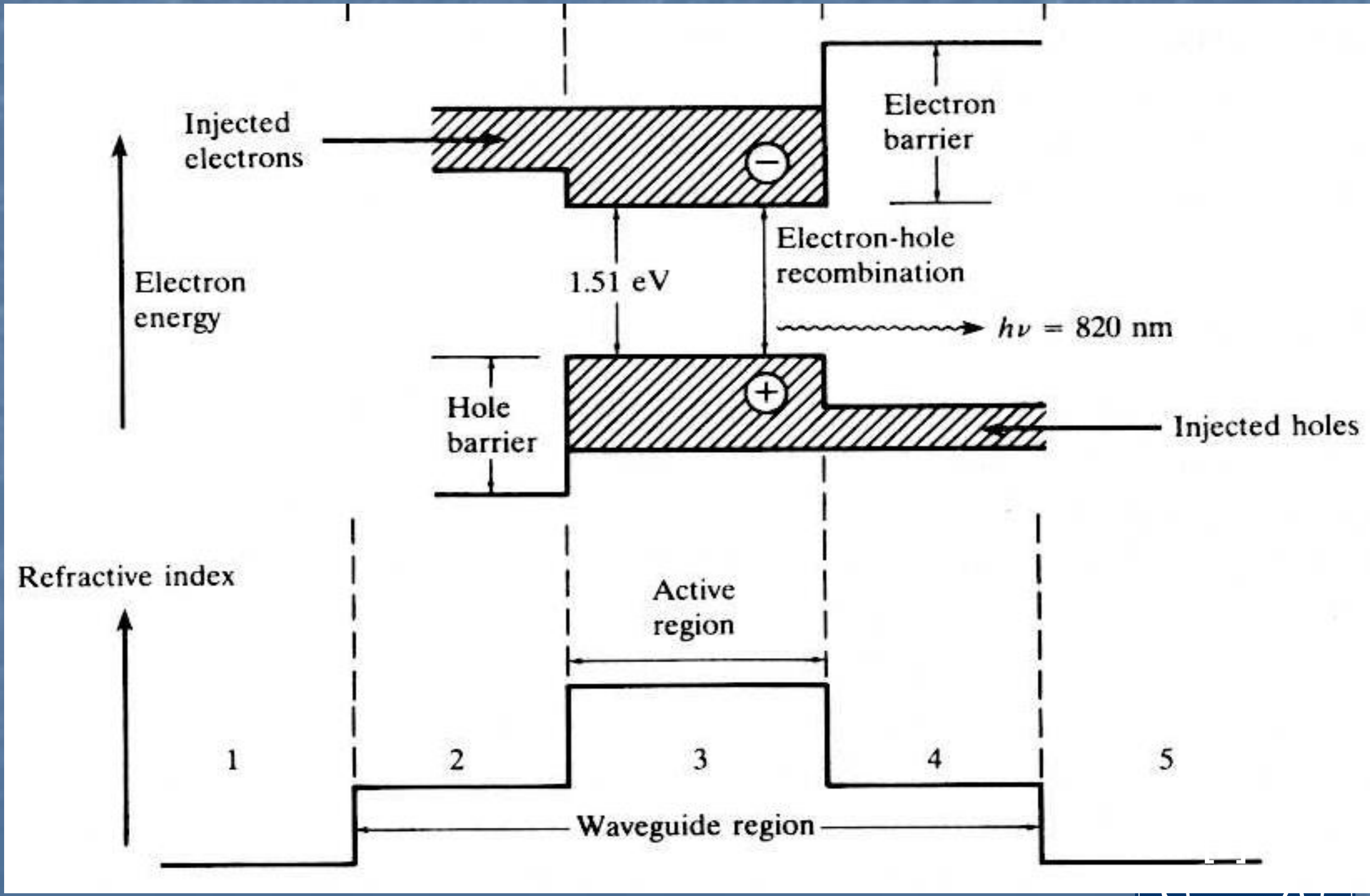
- **Injection luminescence**
- **Competition with non-radiative transitions**
- **External quantum efficiency must be maximised**
- **Coupling efficiency problematic: horizontal, vertical**





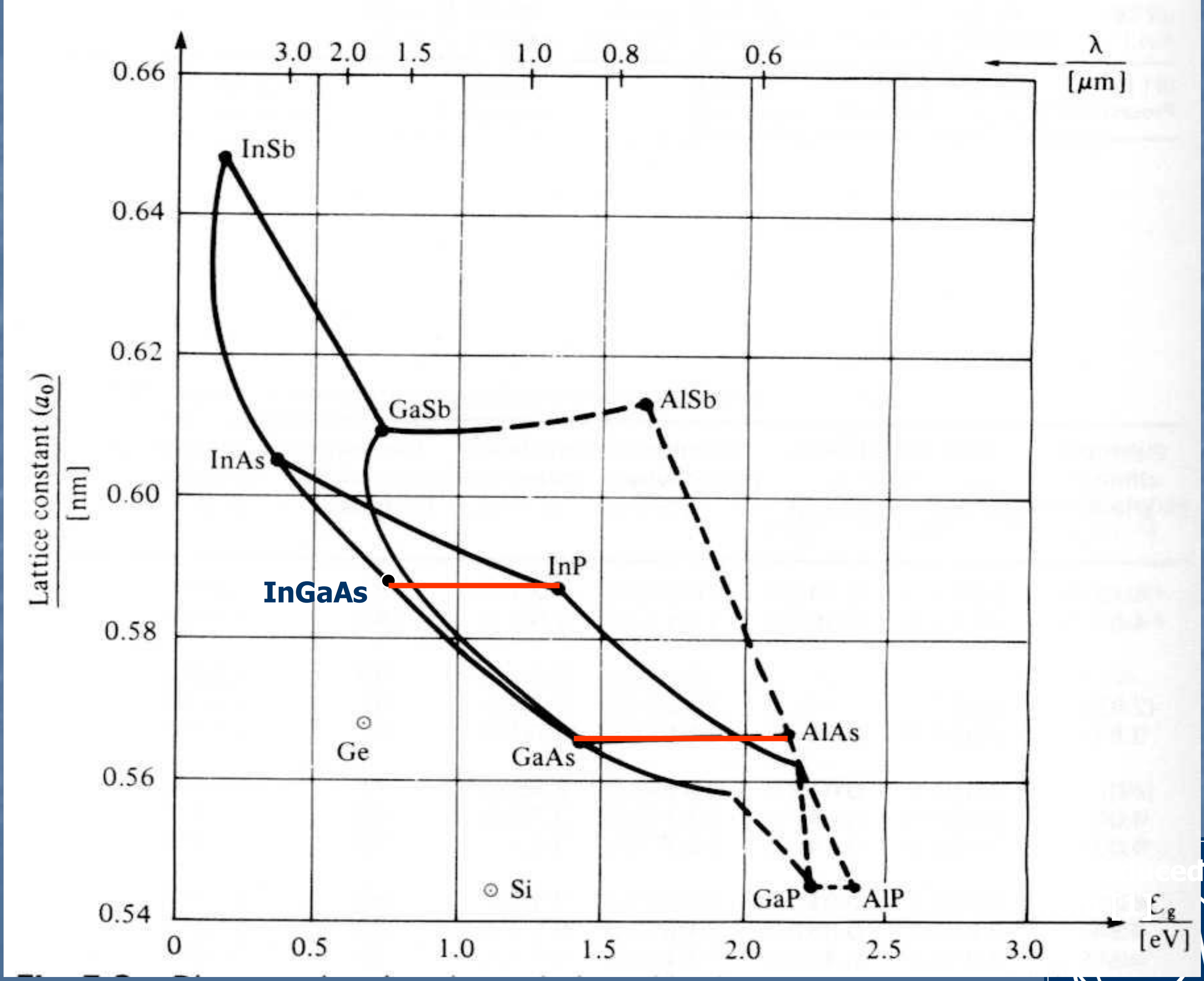
Semiconductor heterostructure

- Modulation by direct injection
- Electrical confinement
- Optical confinement
- Temperature dependence



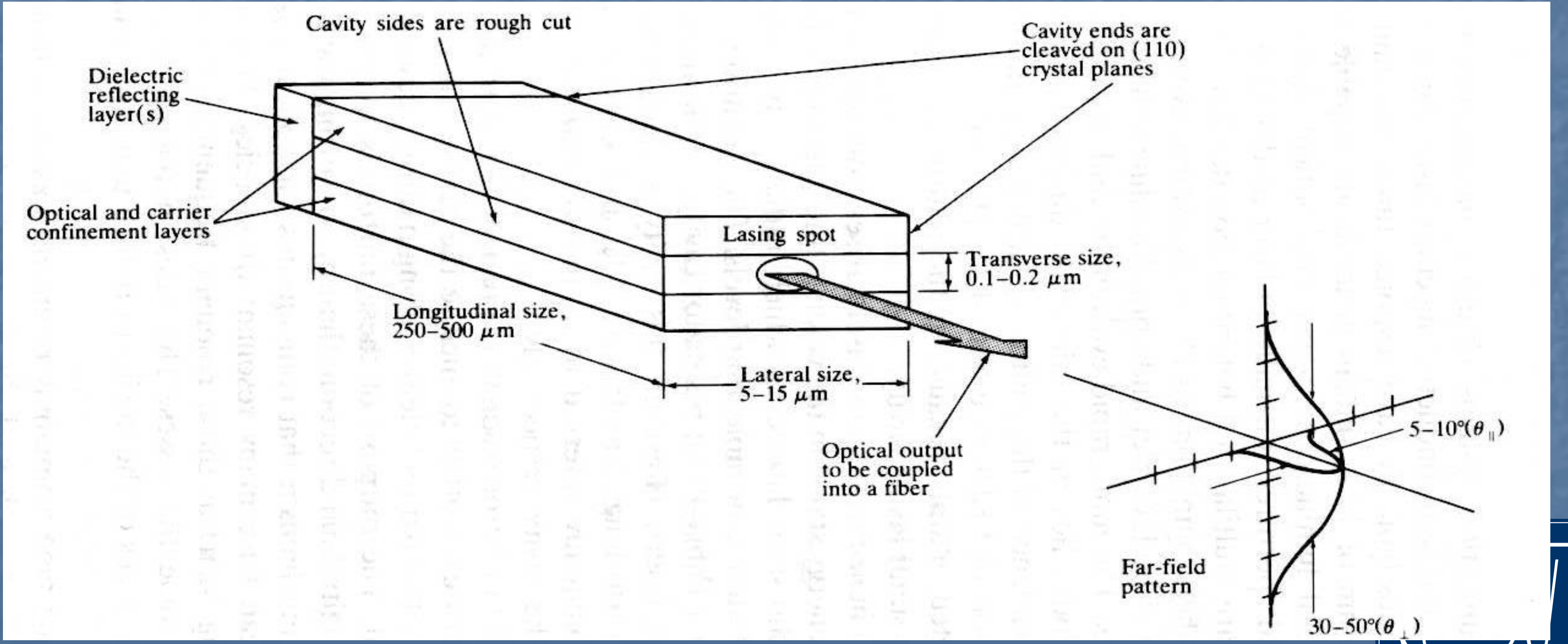
Ternary Material System

- (quasi) lattice matched structures
- Epitaxial growth
- Tight defect control



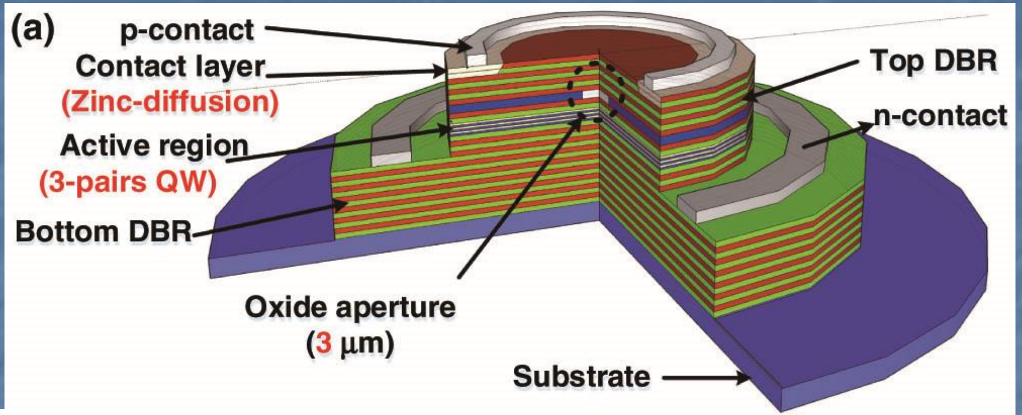
Semiconductor Laser Structure: horizontal cavity

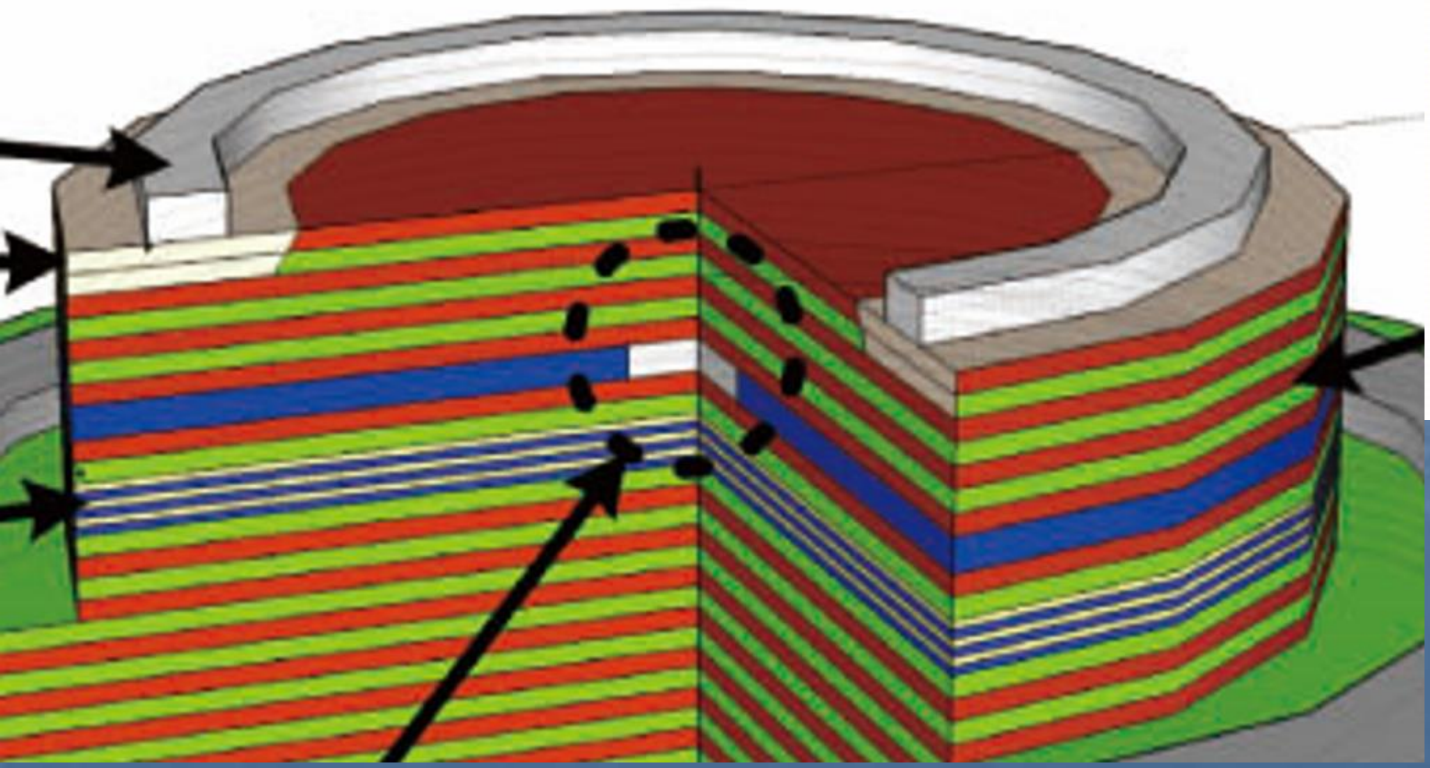
- Narrow Spectrum
- Multiple longitudinal modes
- High modulation bandwidth
- Divergent beam
- Cleaved facets

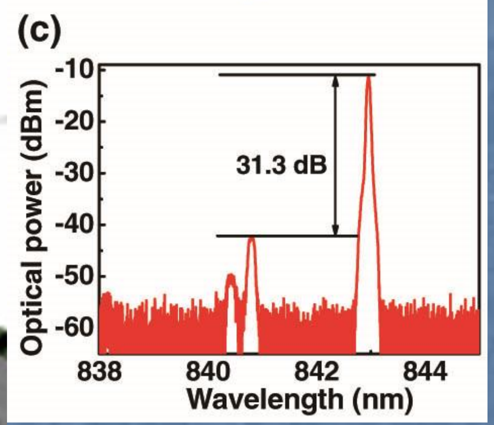


Semiconductor Laser Structure: vertical cavity

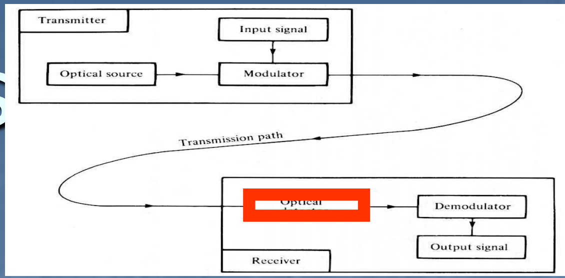
- Single longitudinal mode
- On wafer testing
- Direct coupling to fibre
- Complex epi growth
- Difficult to realize in InP material system



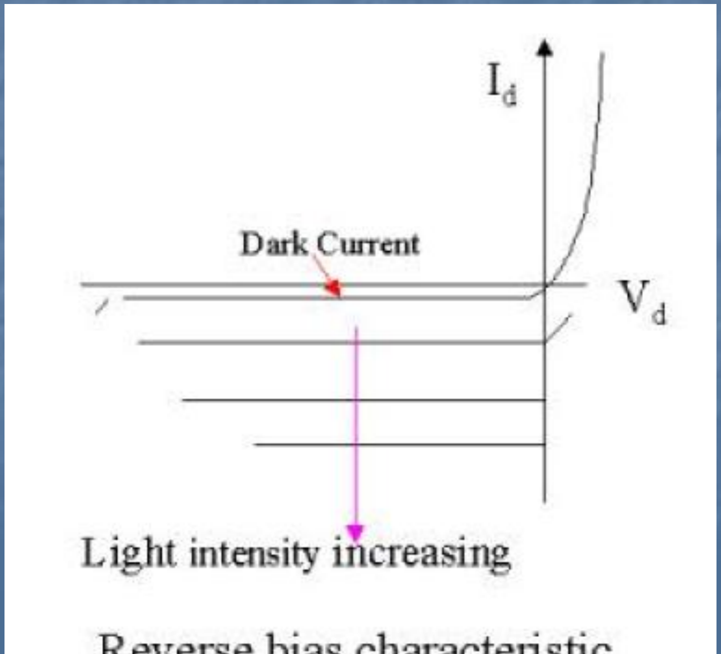




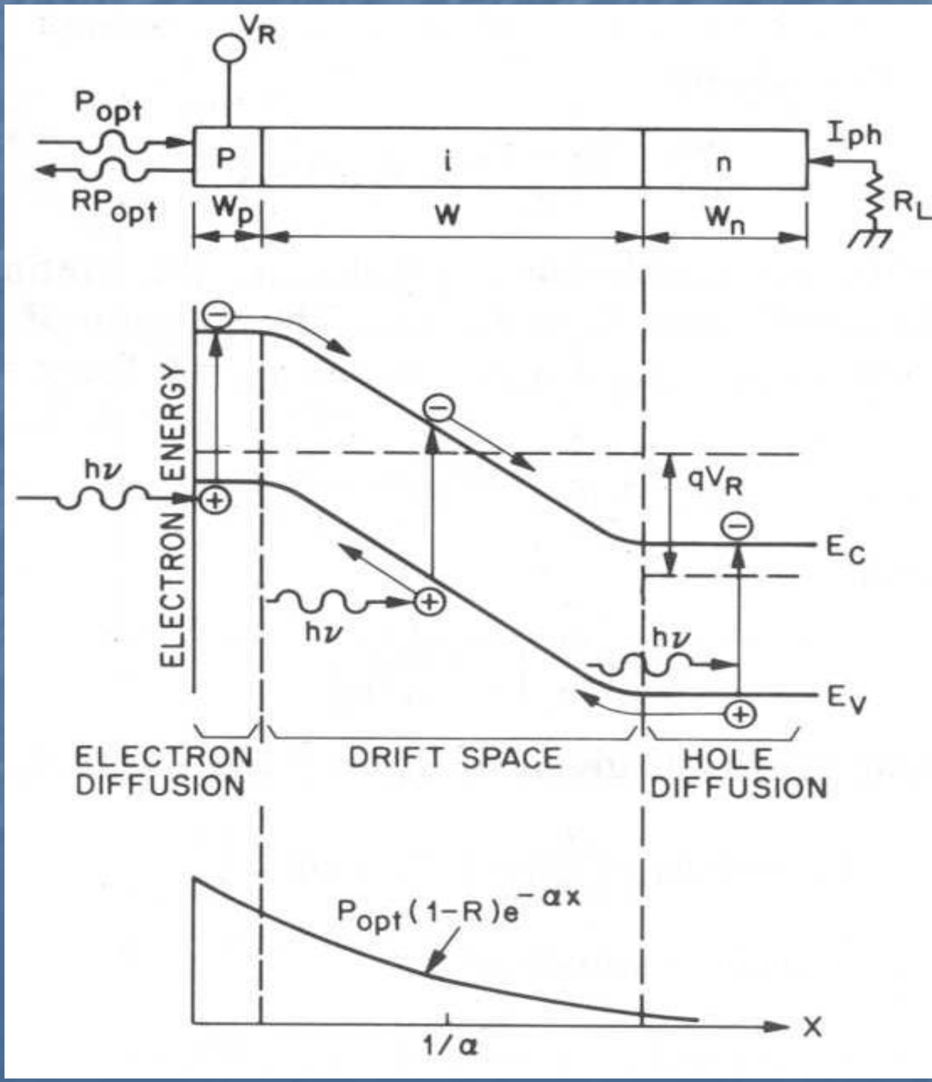
2. Absorption in semiconductors



- Electron-holes separated by bias field
- Absorption depth optimised wrt recombination time
- Capacitance wrt light collection efficiency

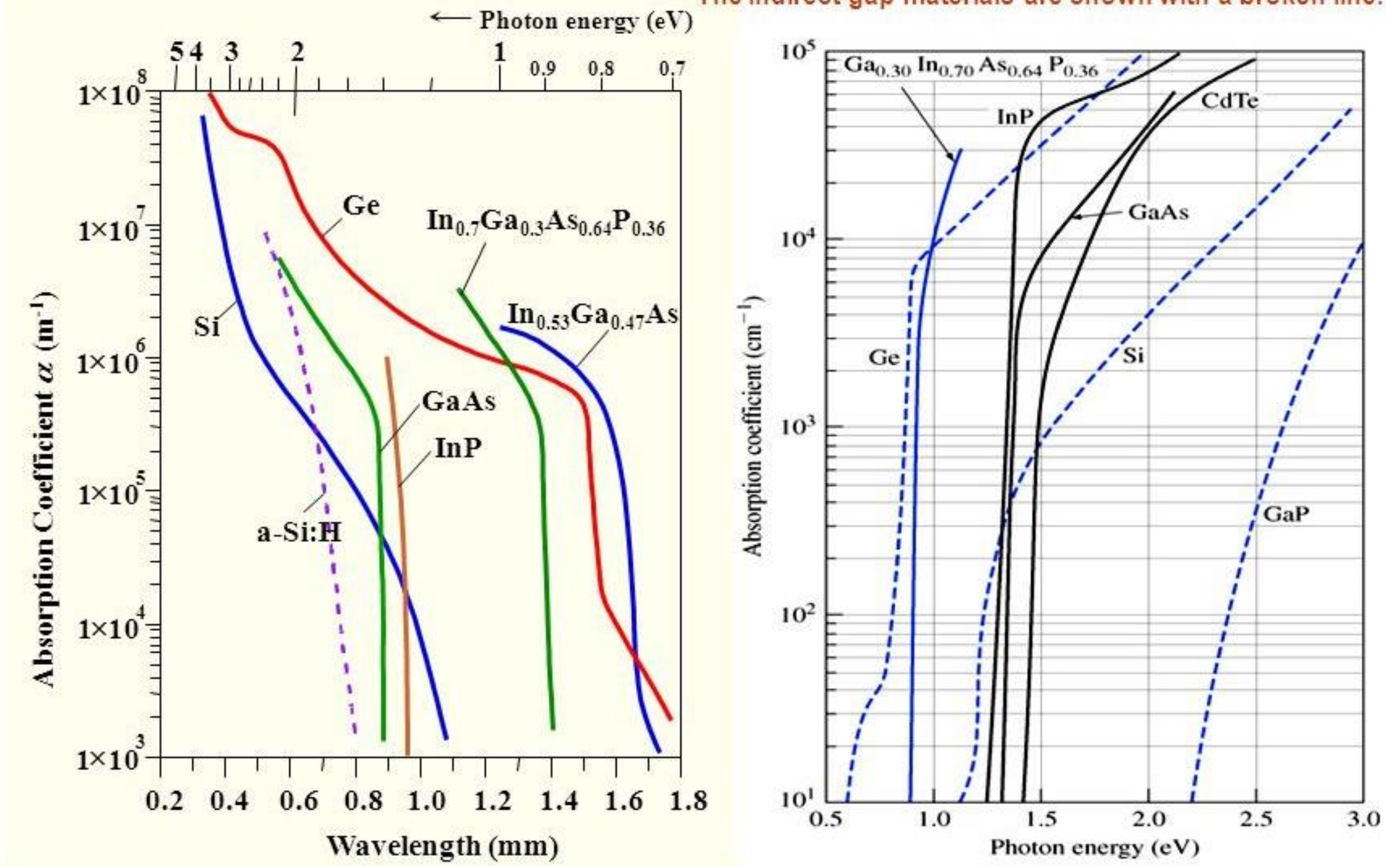


Reverse bias characteristic



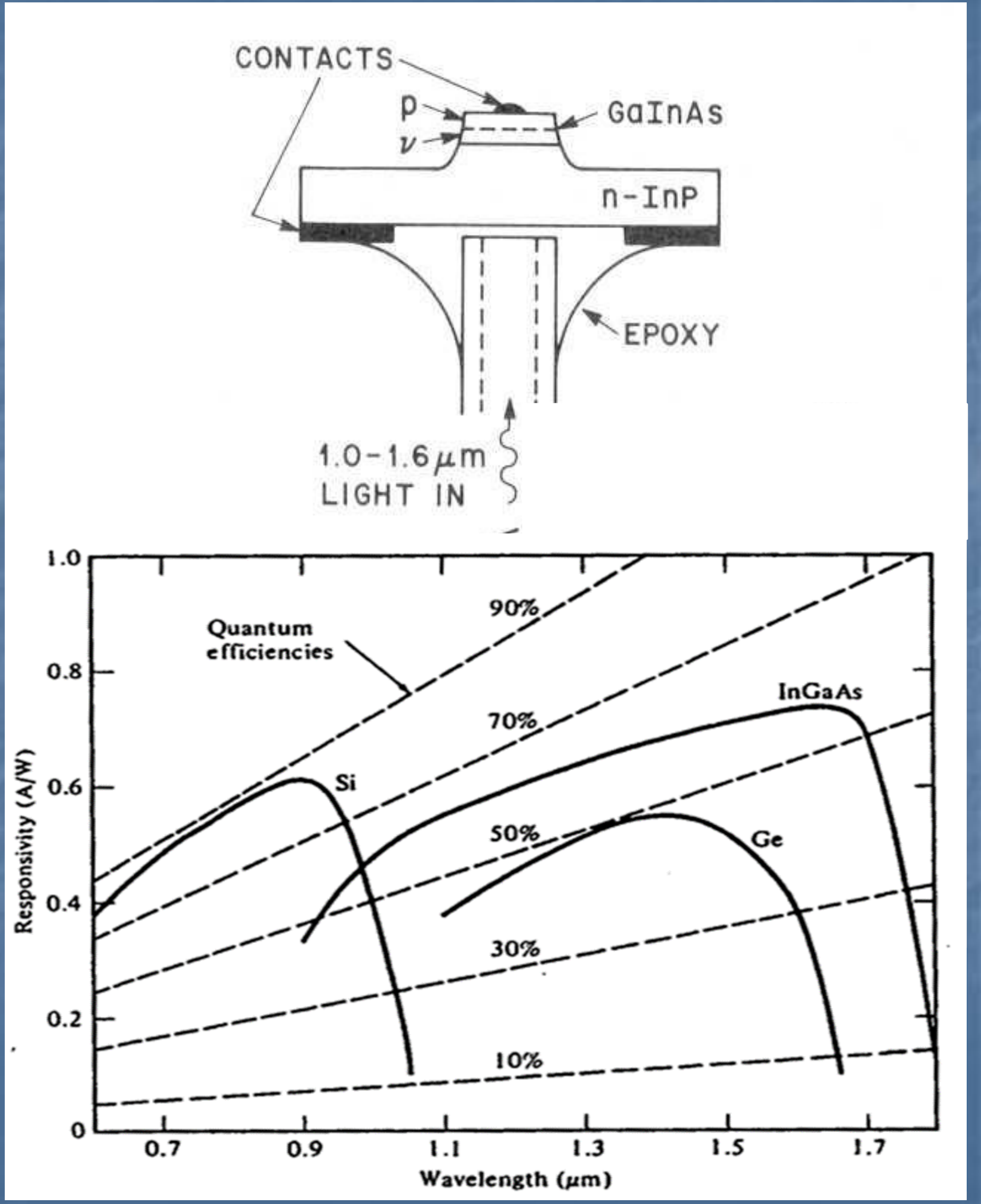
Detector Material Responsivities

The indirect-gap materials are shown with a broken line.

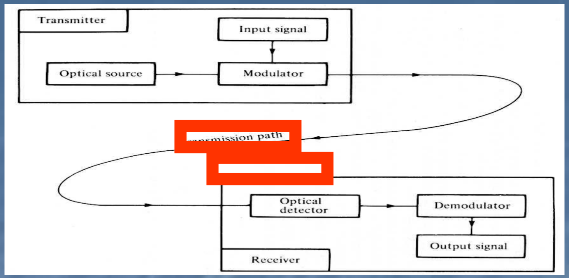


Pin diode

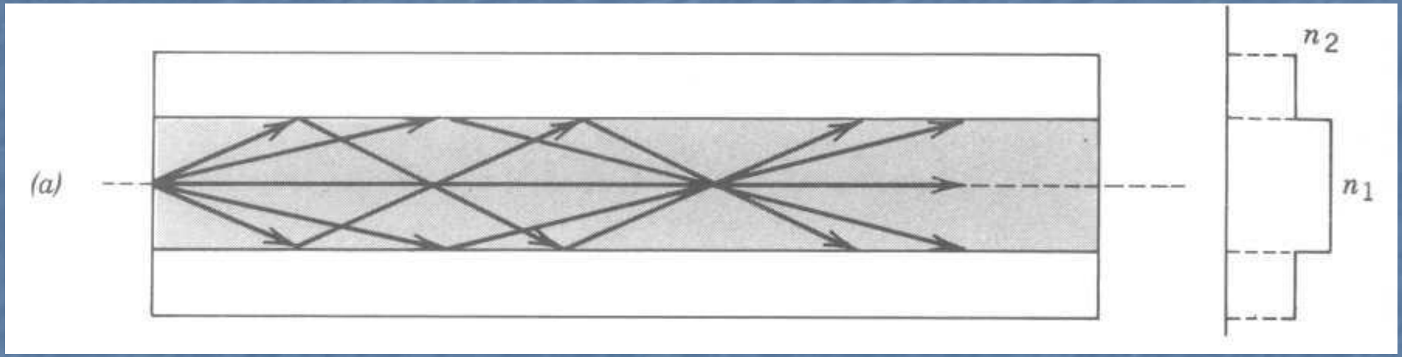
- Vertical access
- Back or front illuminated (transparent substrate)
- Excellent coupling
- Short wavelength response dominated by surface absorption



3. Optical Fibres



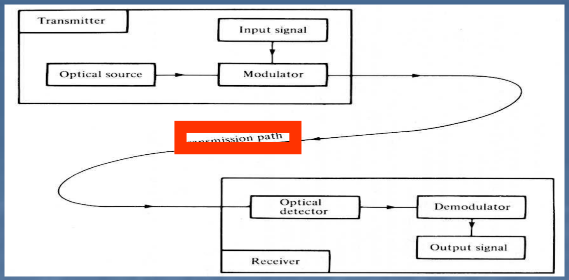
- A discrete set of guided modes propagate
- Most energy in core
- Launch from edge only
- Leakage in bends
- Subject to modal dispersion

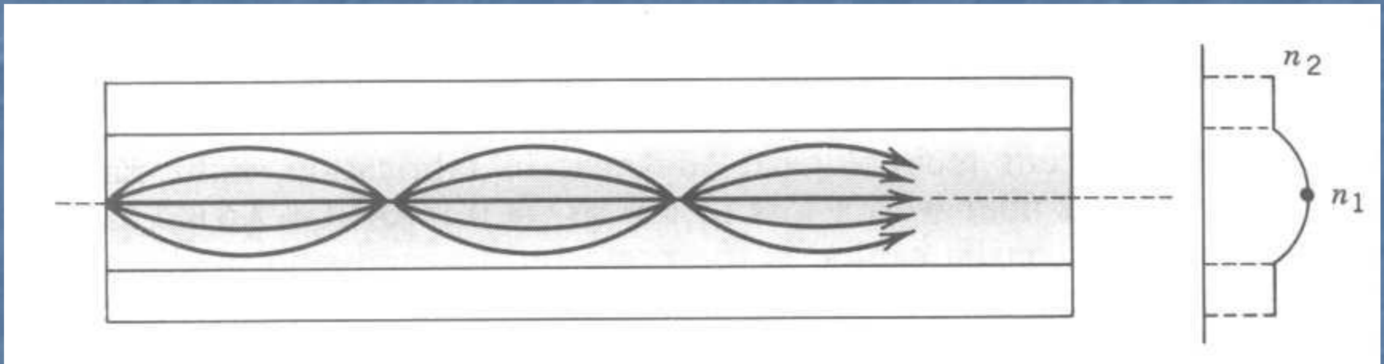


a. Step Index

- Single-mode fibre
- Small core diameter (typ. 9μm)
- Difficult coupling
- Two polarizations

3. Optical Fibres



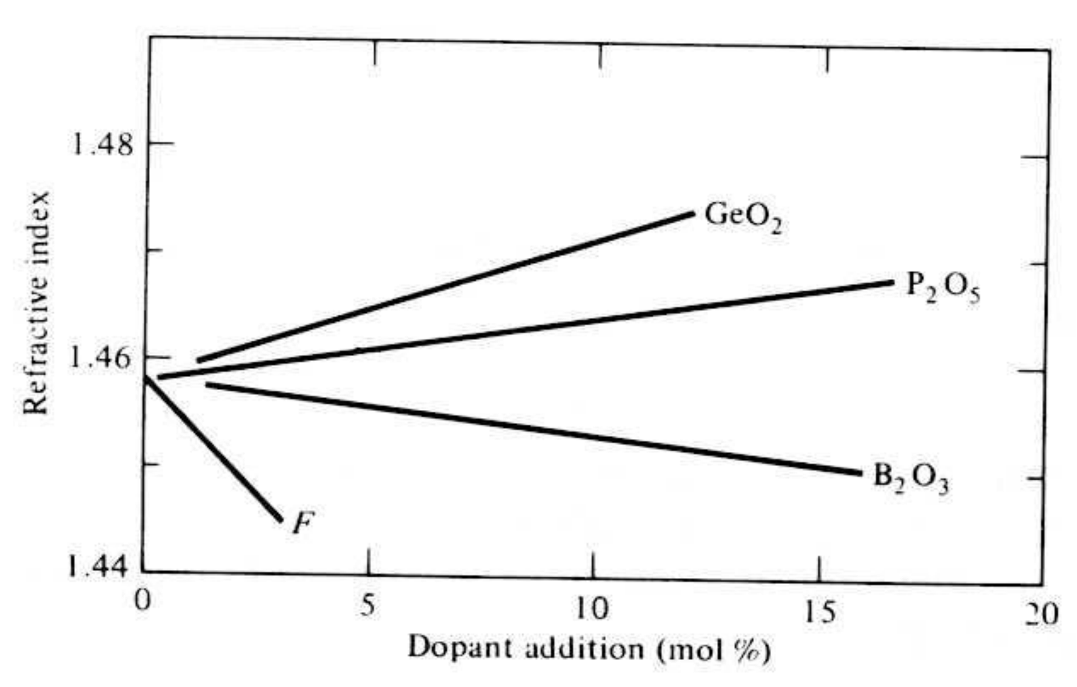


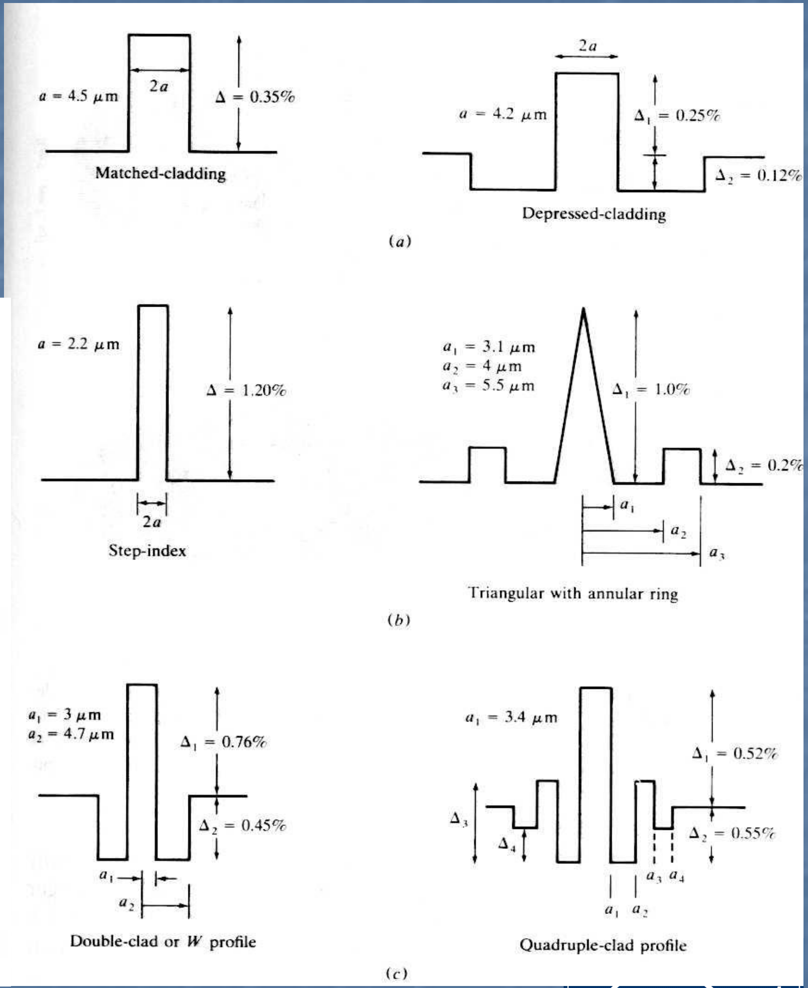
b. Graded Index

- Multi-mode fibre
- Large core diameter (typ. 50μm)
- Equalized phase velocities limit modal dispersion
- Difficult index profile realization
- Easy coupling

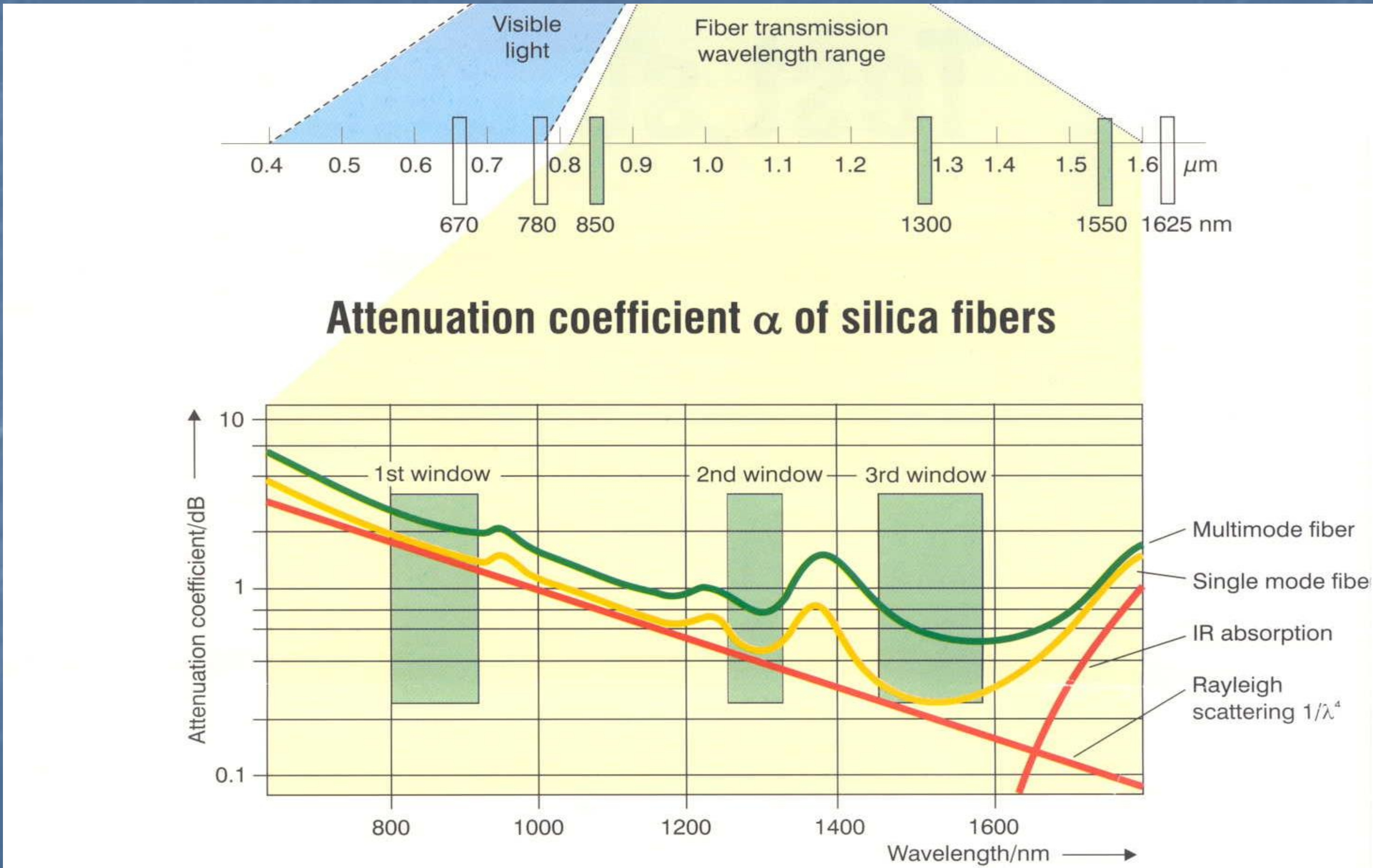
Optical Fibres: material engineering

- Ge-doped core or F-doped cladding
- Waveguide dispersion engineering

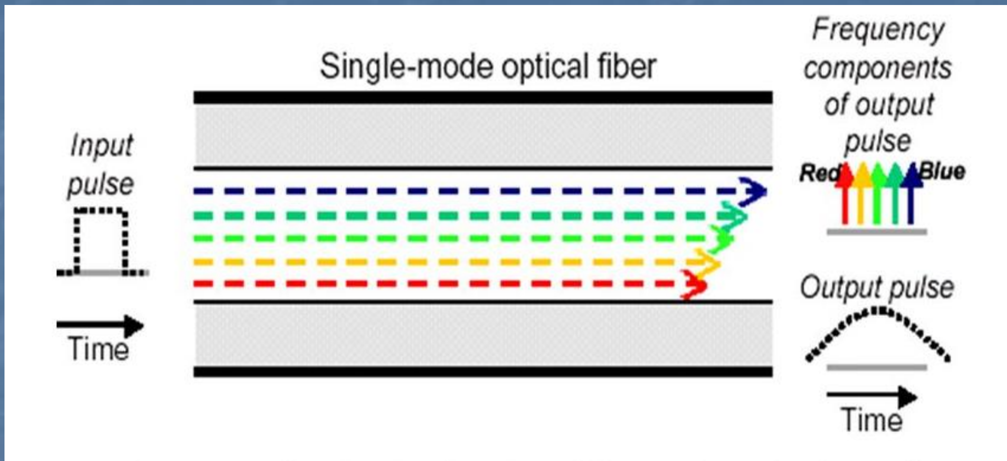




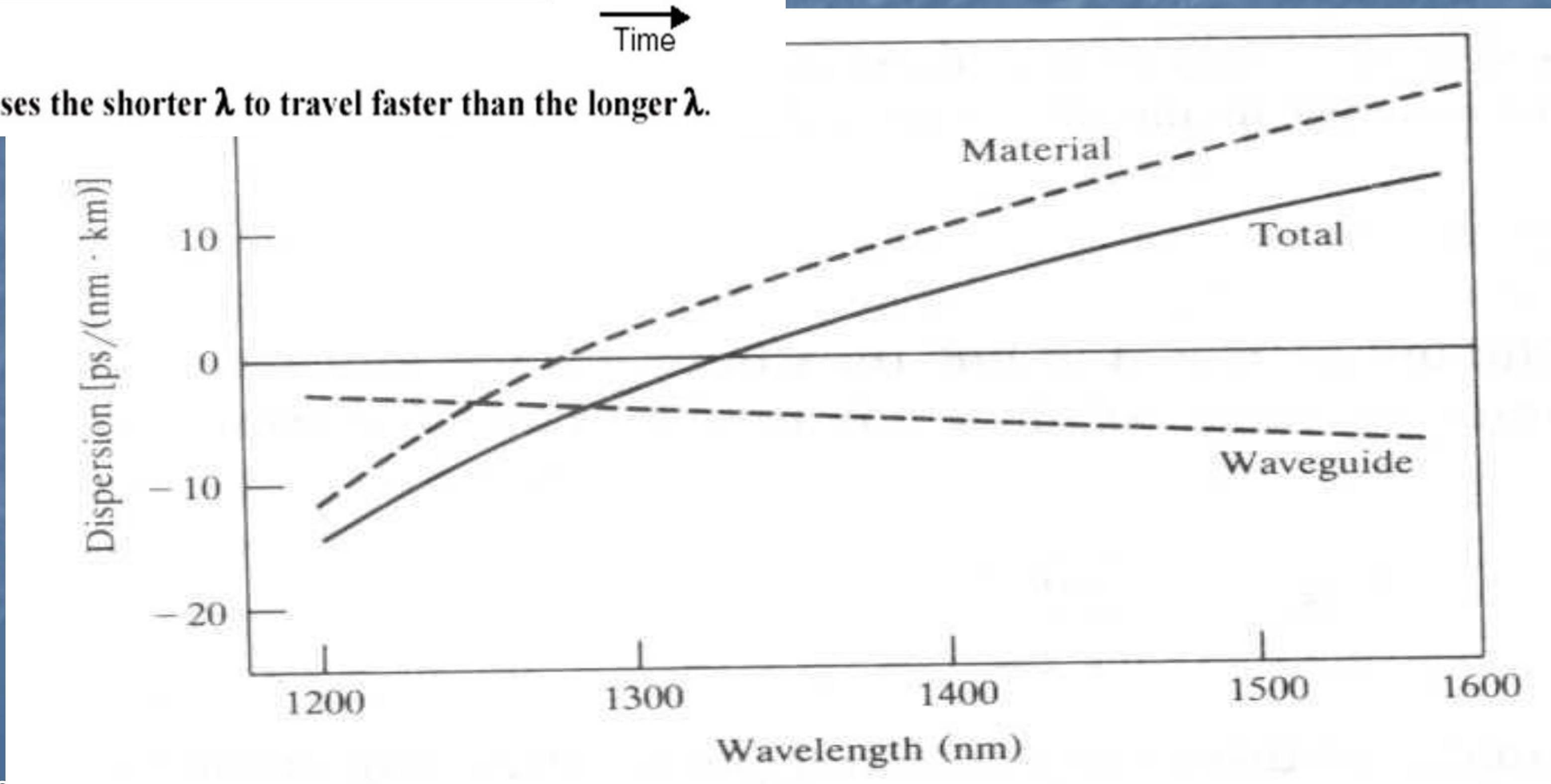
Silica transmission windows



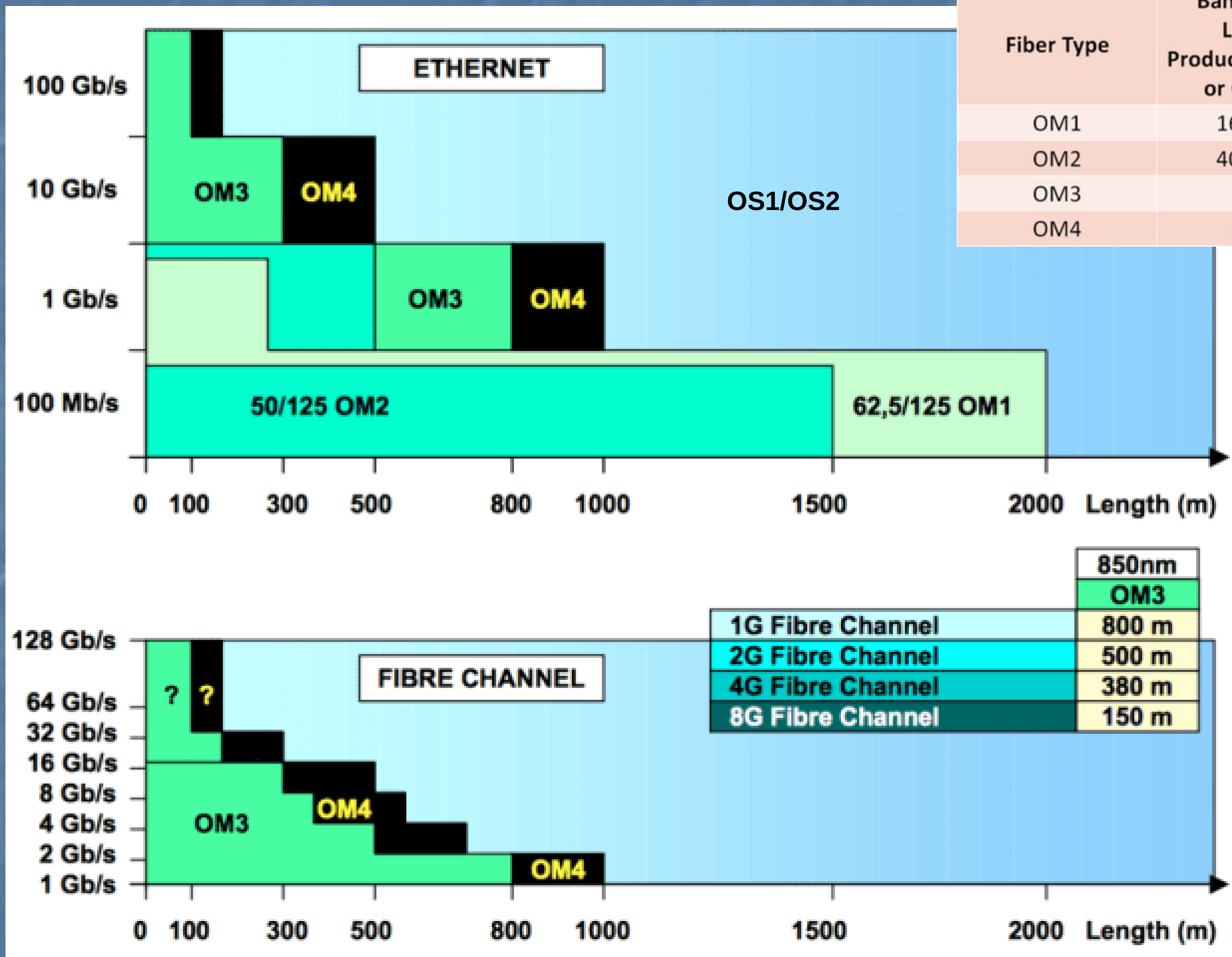
Optical Fibres: Dispersion



CD causes the shorter λ to travel faster than the longer λ.



Optical Systems: Speed and Range



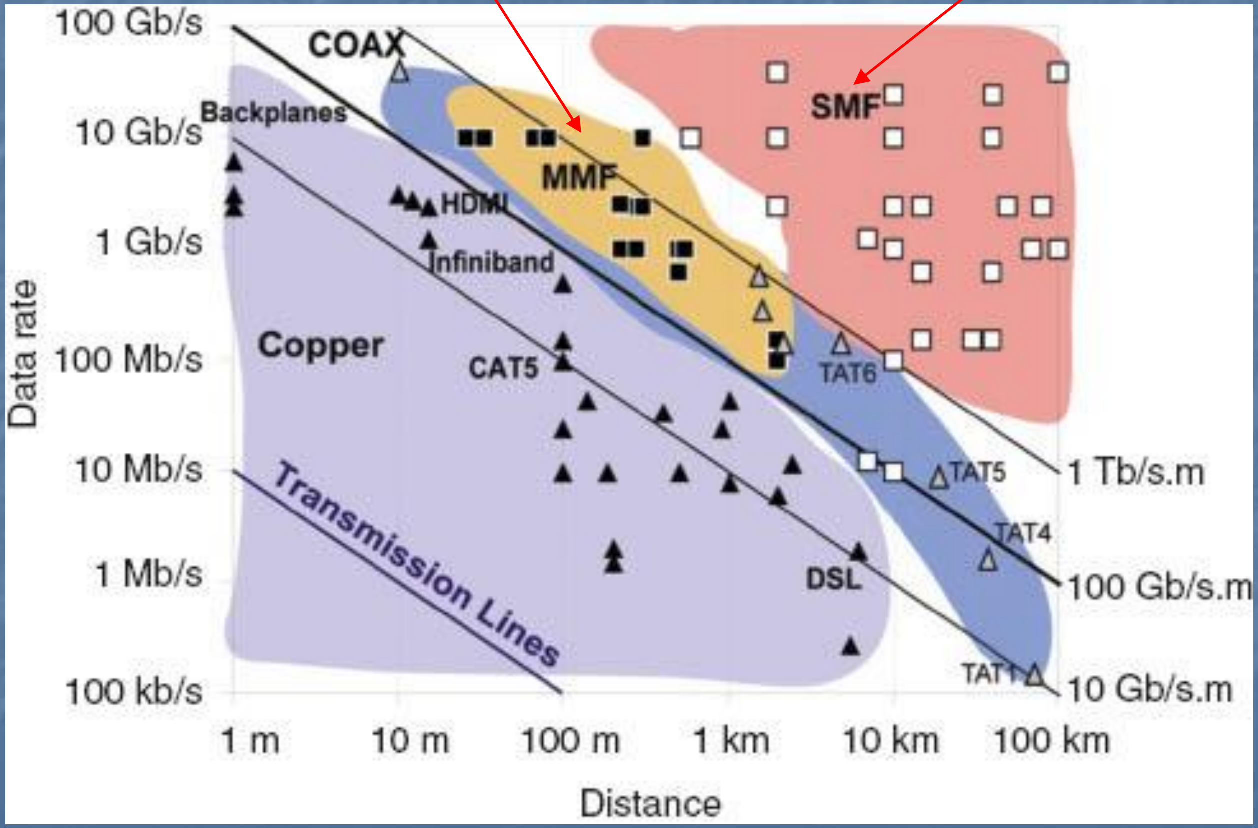
FIBER TYPES AND REACH			
Fiber Type	Bandwidth/ Length Product (MHz/km or GHz/m)	10GBASE-SR Distance (meters)	40GBASE-SR4 and 100GBASE-SR10 Distance (meters)
OM1	160-200	33	N/A
OM2	400-500	82	N/A
OM3	2000	300	100
OM4	4700	400	150

- Dispersion (and attenuation) will limit MM systems to short distances
- Low cost will dictate the use of VCSELs at 850nm (1st window)
- As speed increases new MM fiber must be developed to maintain distance)

Optical Fibers: Capacity [Datarate×distance]

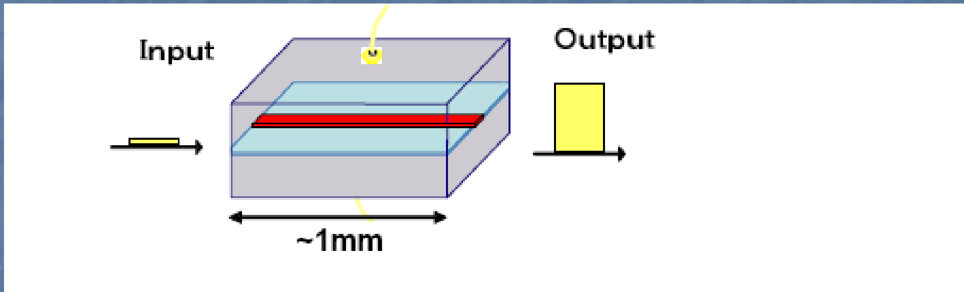
Multi Mode Fibre
VCSEL, AlGaAs
850nm

Single Mode Fibre
Edge Emitting Laser, InGaAsP
1310-1550nm

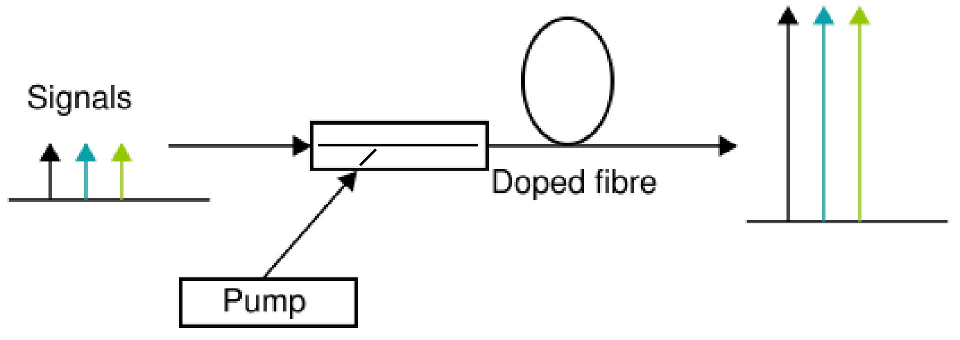


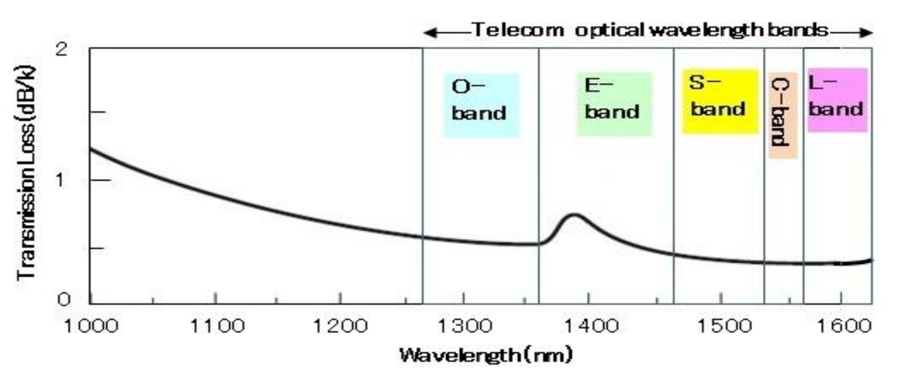
4. Light Amplification

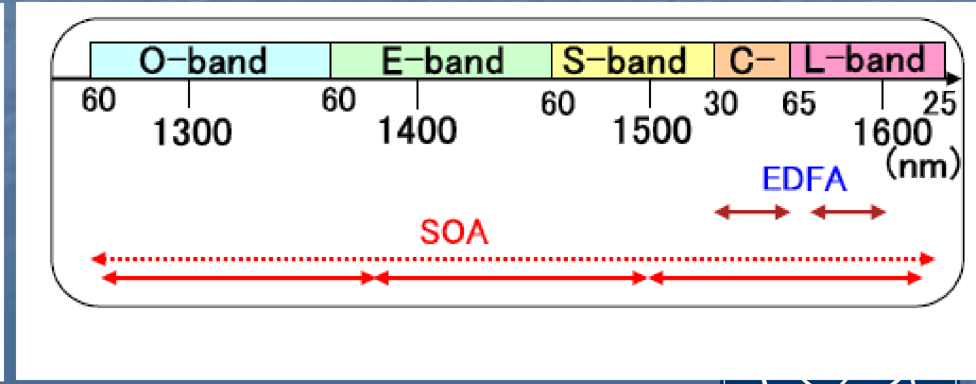
1) Semiconductor Optical Amplifiers (SOA)



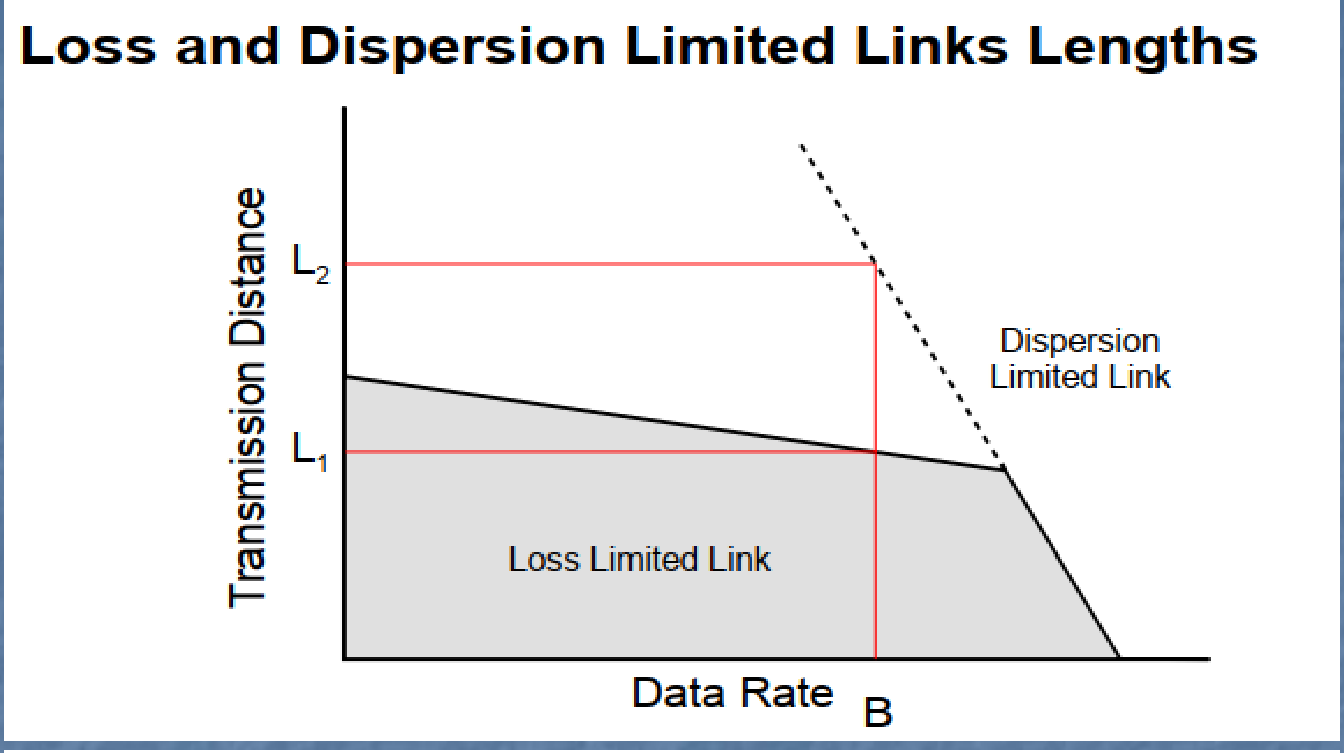
2) Erbium doped fiber amplifiers (EDFA)

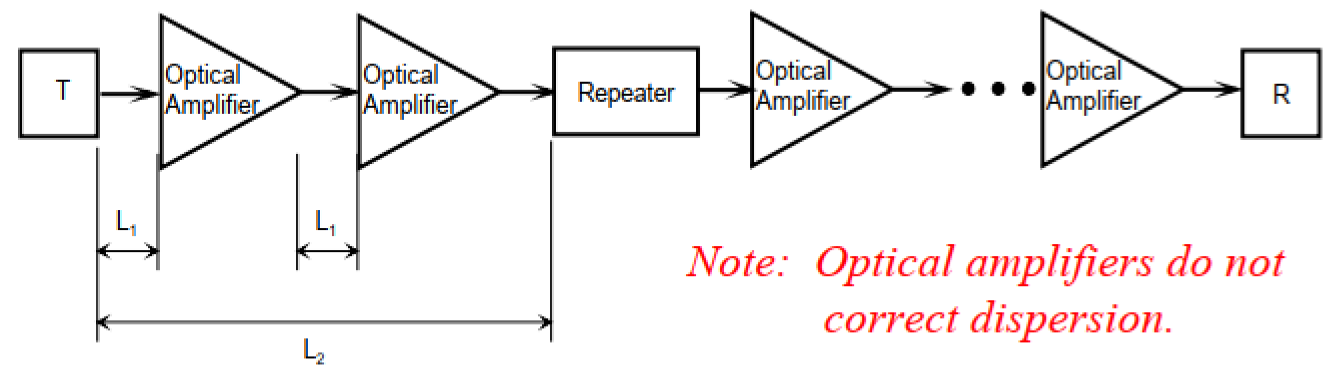






Extending reach with optical amplifiers

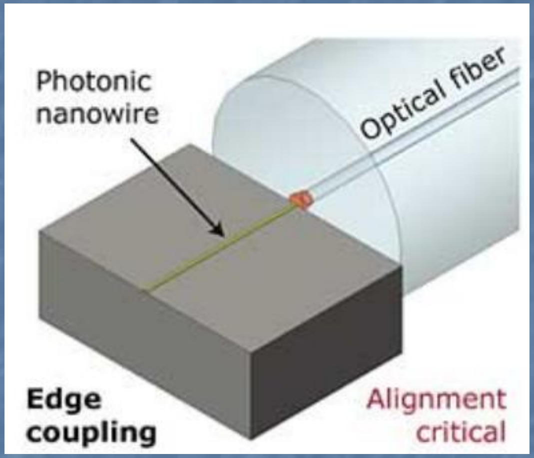




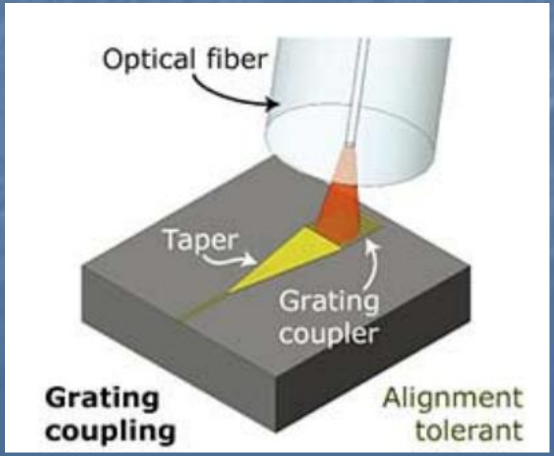
Note: Optical amplifiers do not correct dispersion.

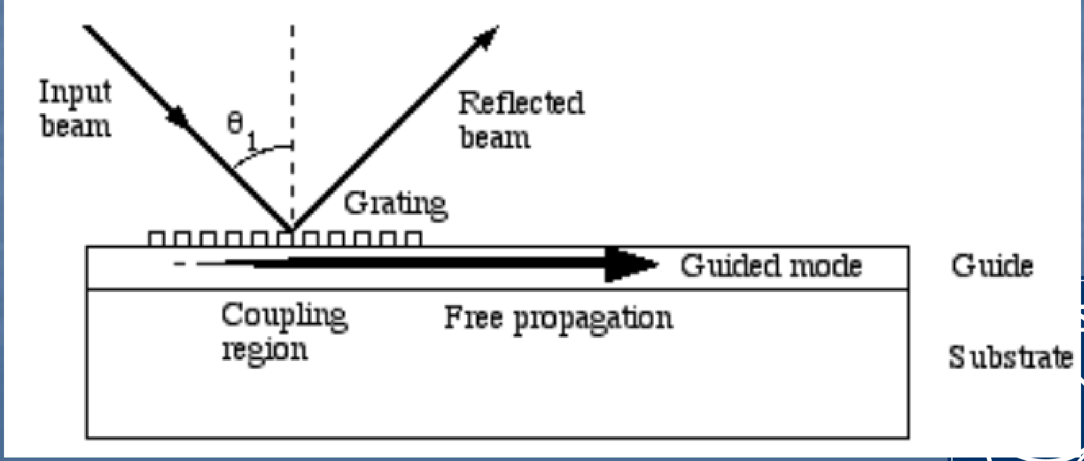
5. Light in/out coupling

- Edge coupling

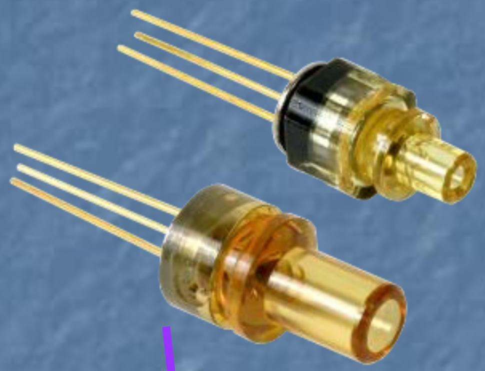


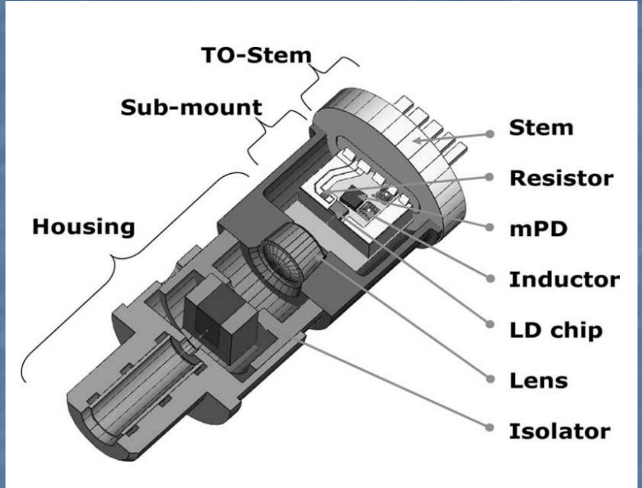
- Grating coupling





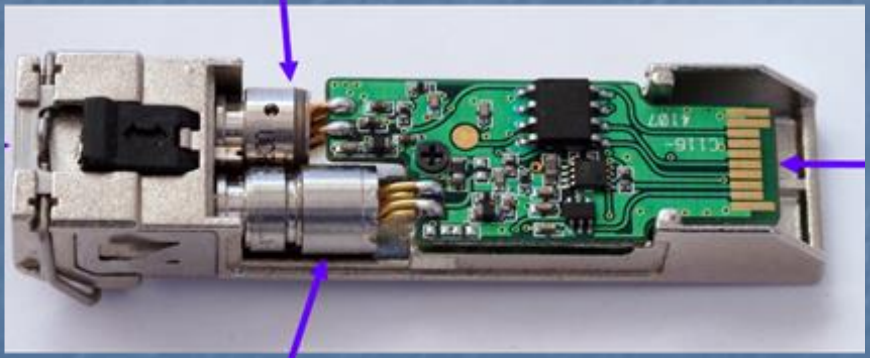
6. Packaging: Optical Subassemblies (OSA)





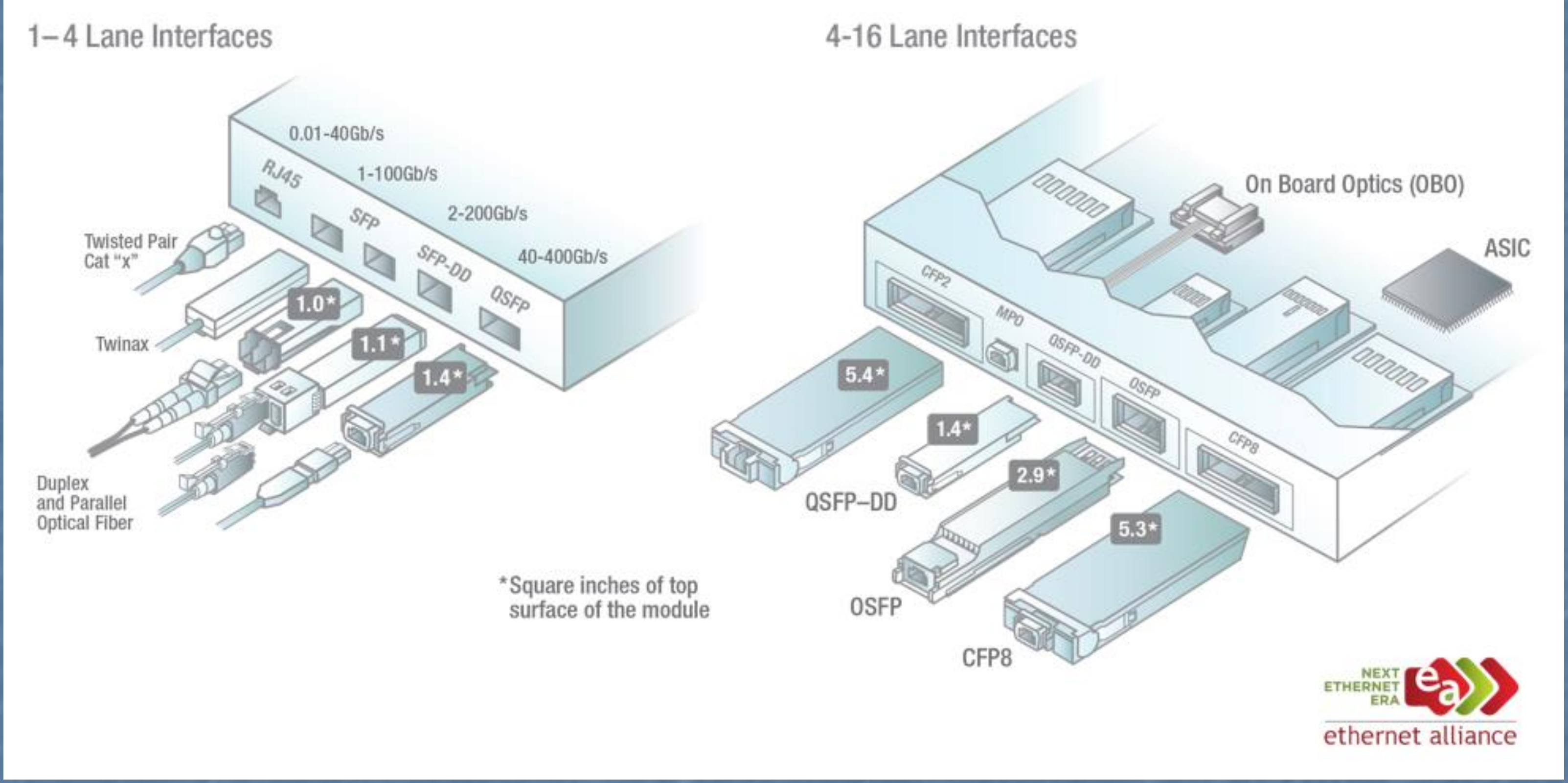
Fabricated TOSA structure in XFP transceiver module.

ROSA – Receiver Optical Sub-Assembly



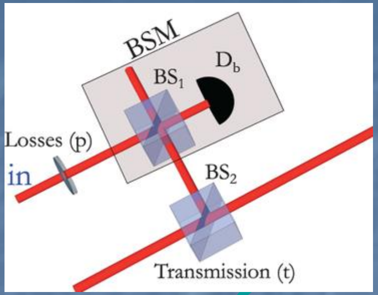
TOSA – Transmitter Optical Sub-Assembly

Packaging: Transceiver form factors

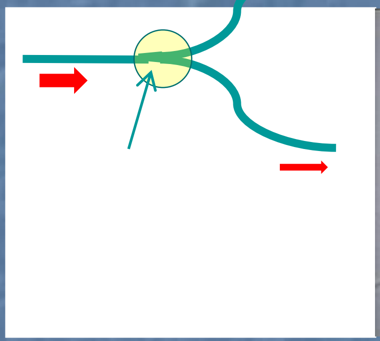


7. Light Splitting and Processing

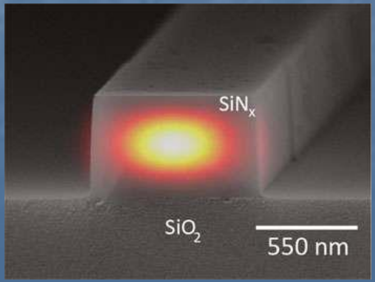
- Bulk optics

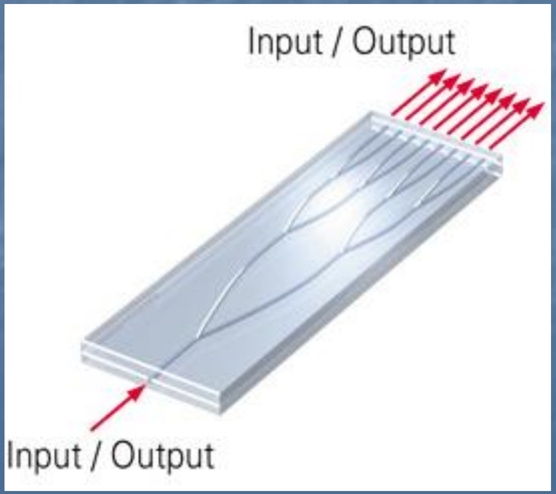


- Bi-conic fused silica splitter



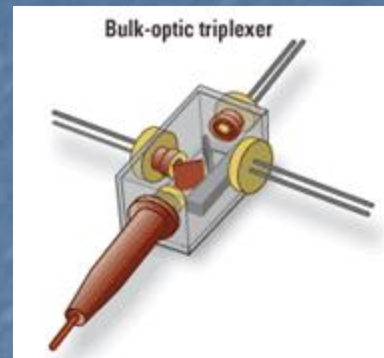
- Photonic lightwave circuit (PLC)
  - Glass
  - Silicon Nitride
  - Si photonics

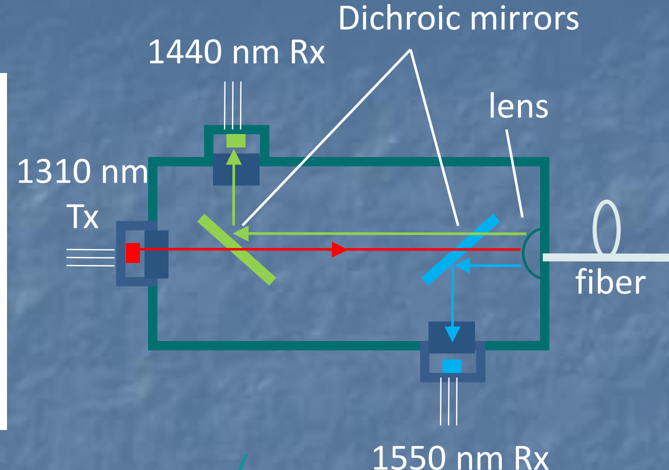




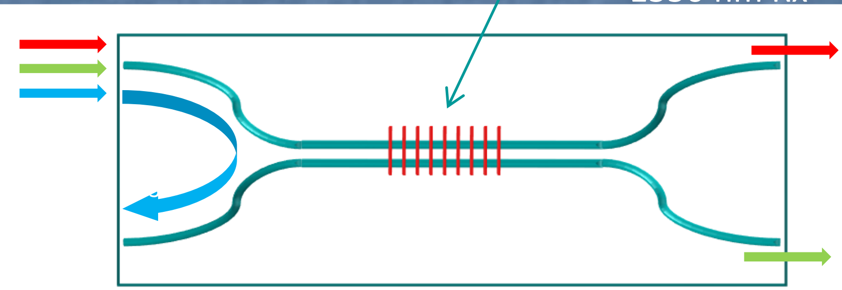
Wavelength Multiplexers/Demultiplexers

- Bulk optics (thin films)

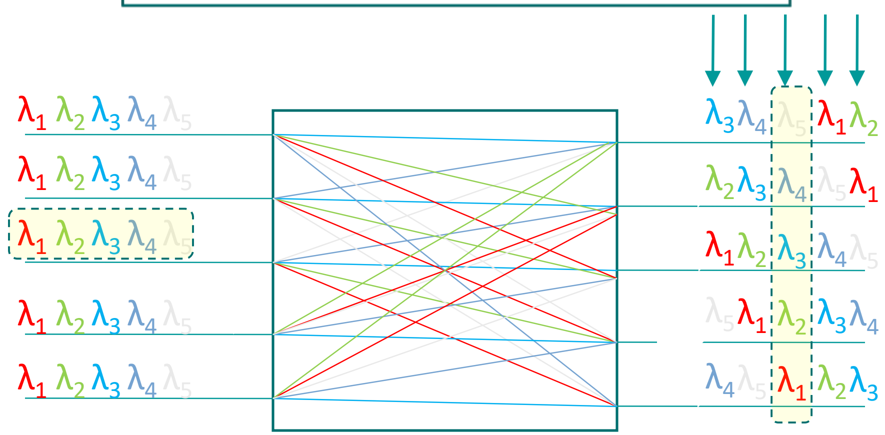




- Planar Lightwave Circuit (PLC)
- Fiber Bragg Gratings

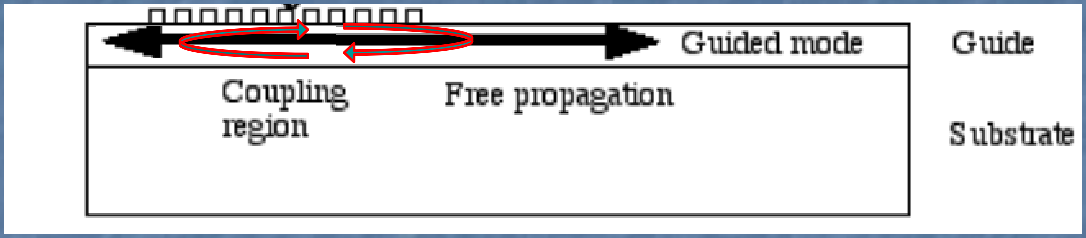


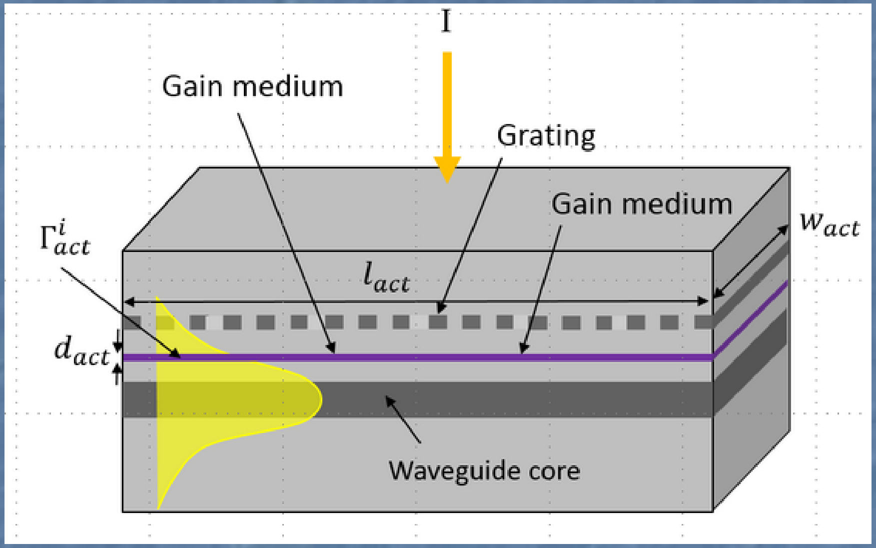
- Arrayed Waveguide Gratings (AWG)

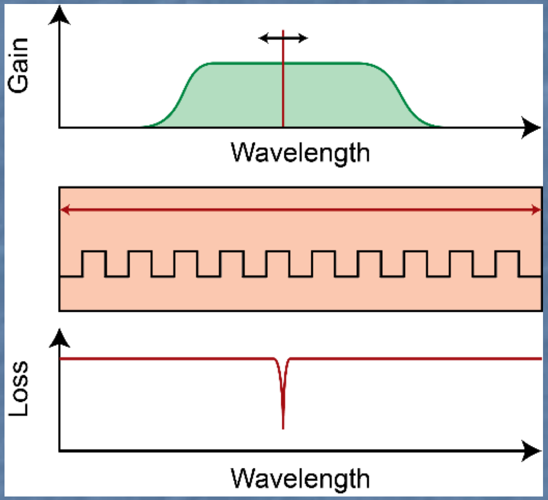


Adding wavelength selectivity to a Laser

- Distributed Feedback and Distributed Bragg laser

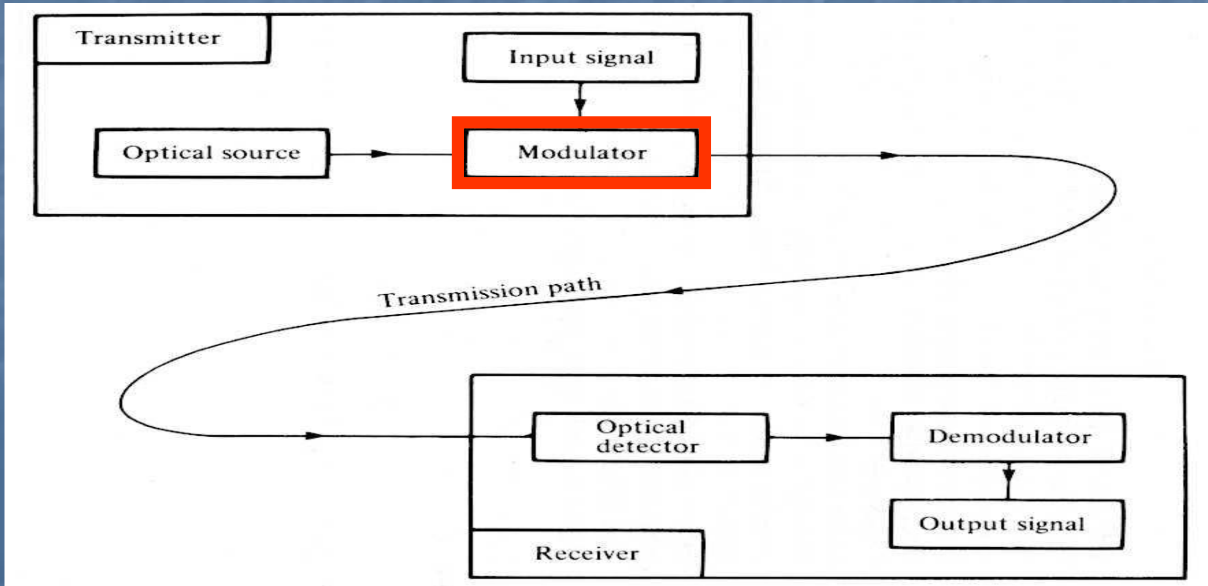






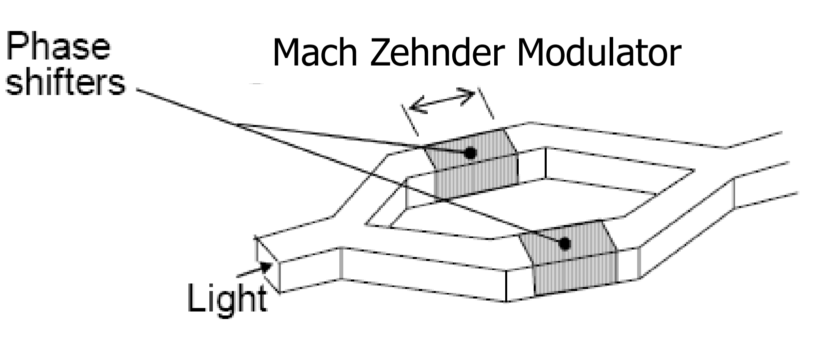
Technology: Modulation Formats

- Context
- Technology
  - Networks
  - Hardware Toolbox
  - Modulation Formats
  - Capacity
  - Standards
- HEP Specifics

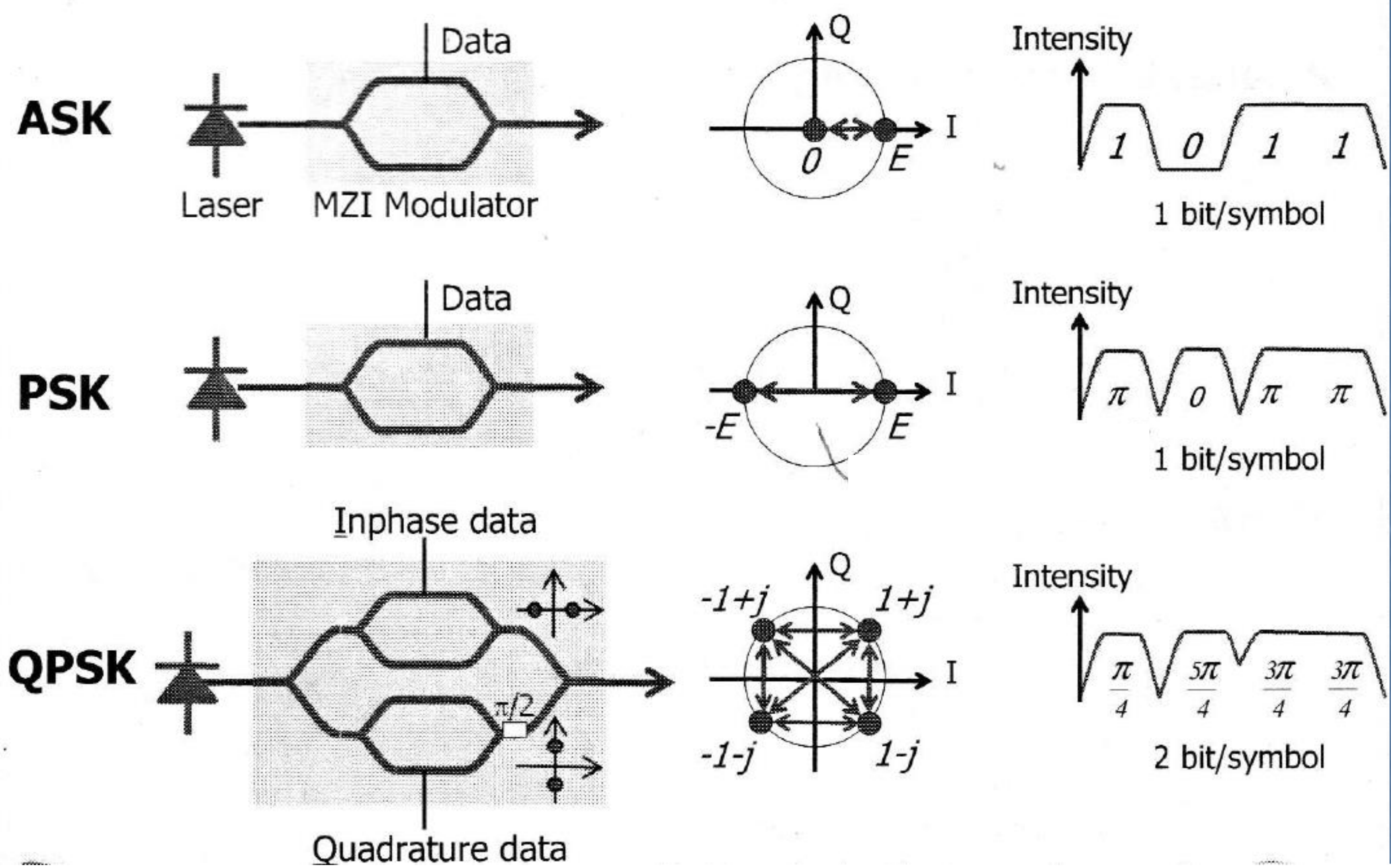


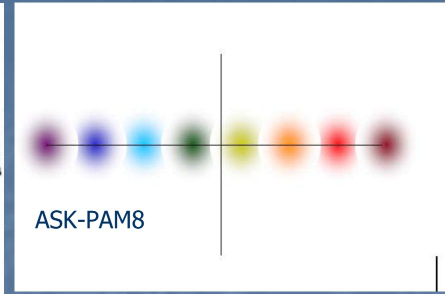
Modulation

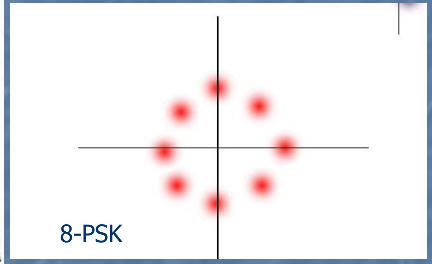
- Direct Modulation
  - Limited by:
    - Carrier lifetime
    - Wavelength chirp
- Indirect Modulation
  - Phase modulation
    - EO effect in crystals (LiNbO3)
    - Free carrier injection in pin (Si)
  - Intensity modulation
    - PM + Interferometer
    - Electro absorption



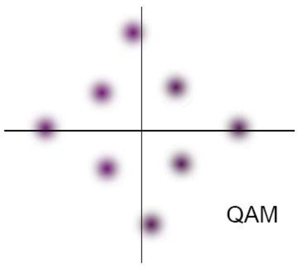
Common modulation techniques



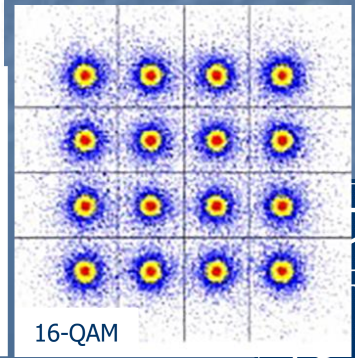




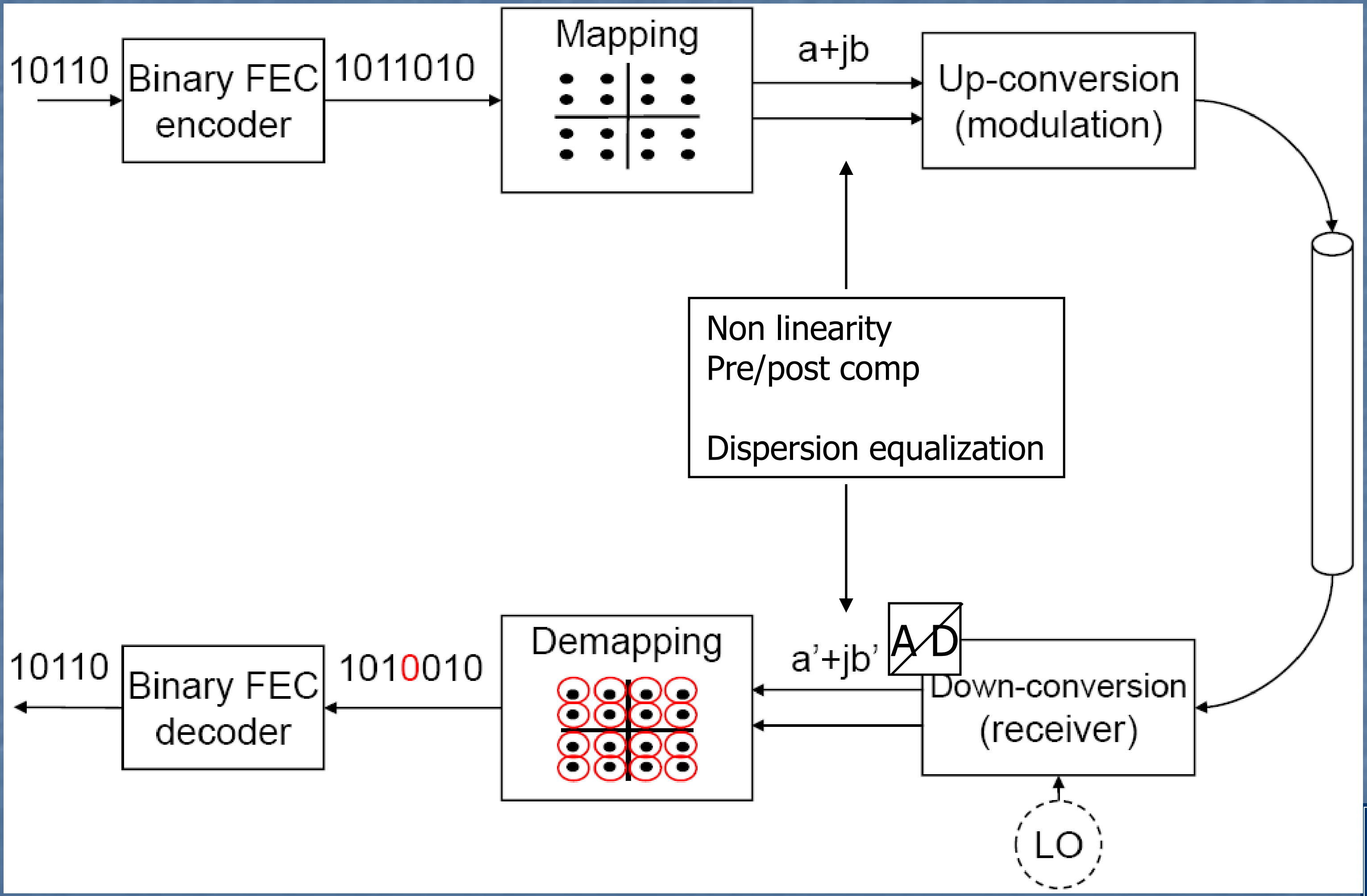
QAM



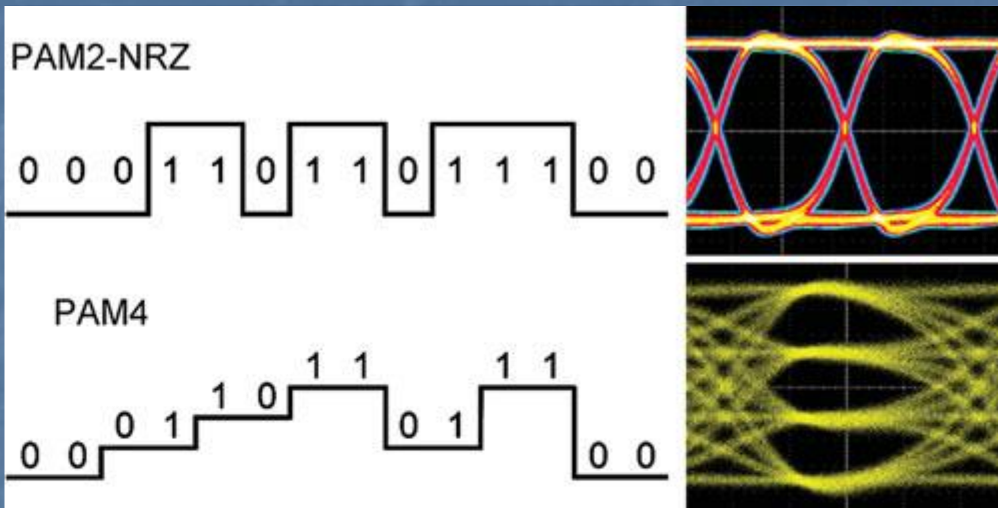
SNR
Detection Complexity

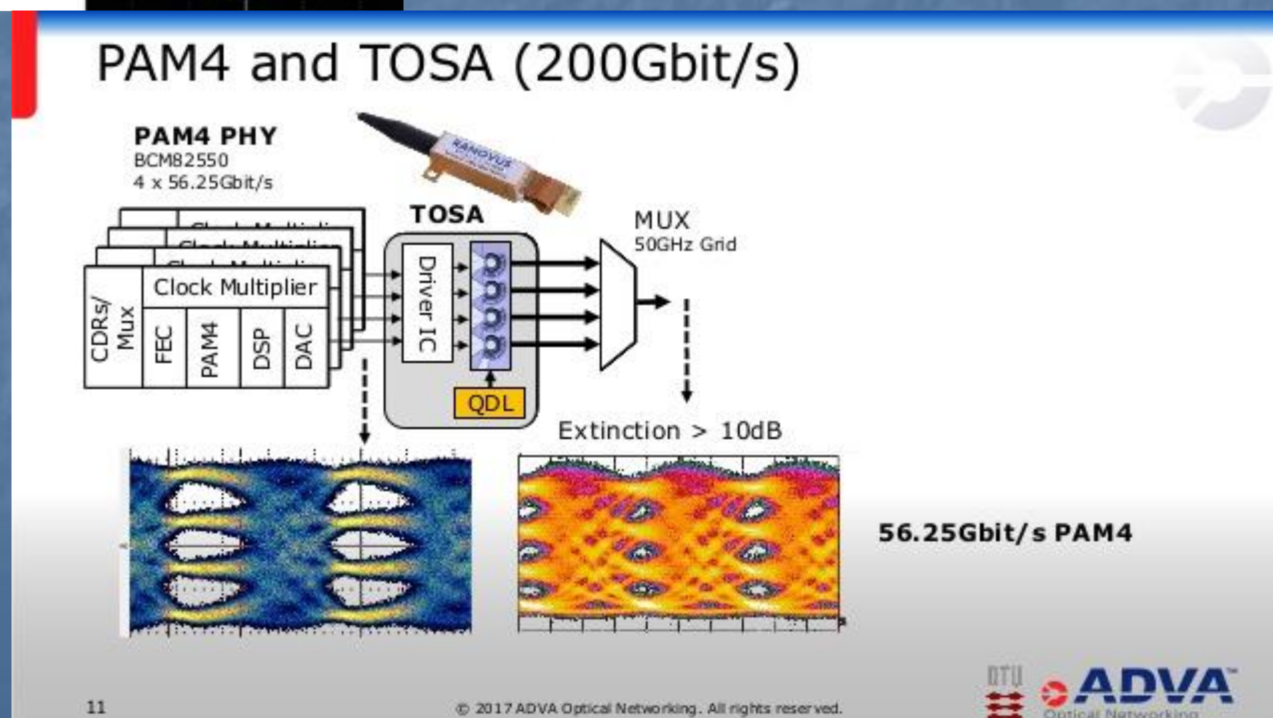


Implementation example 1: QAM16



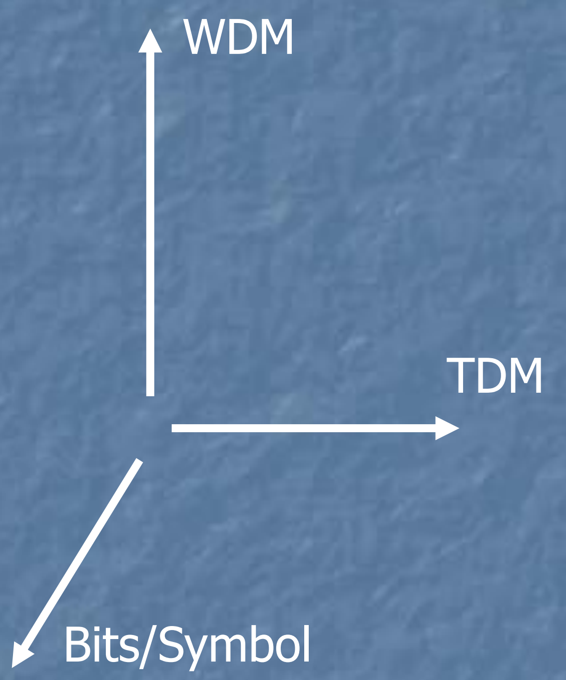
Implementation example 2: PAM4



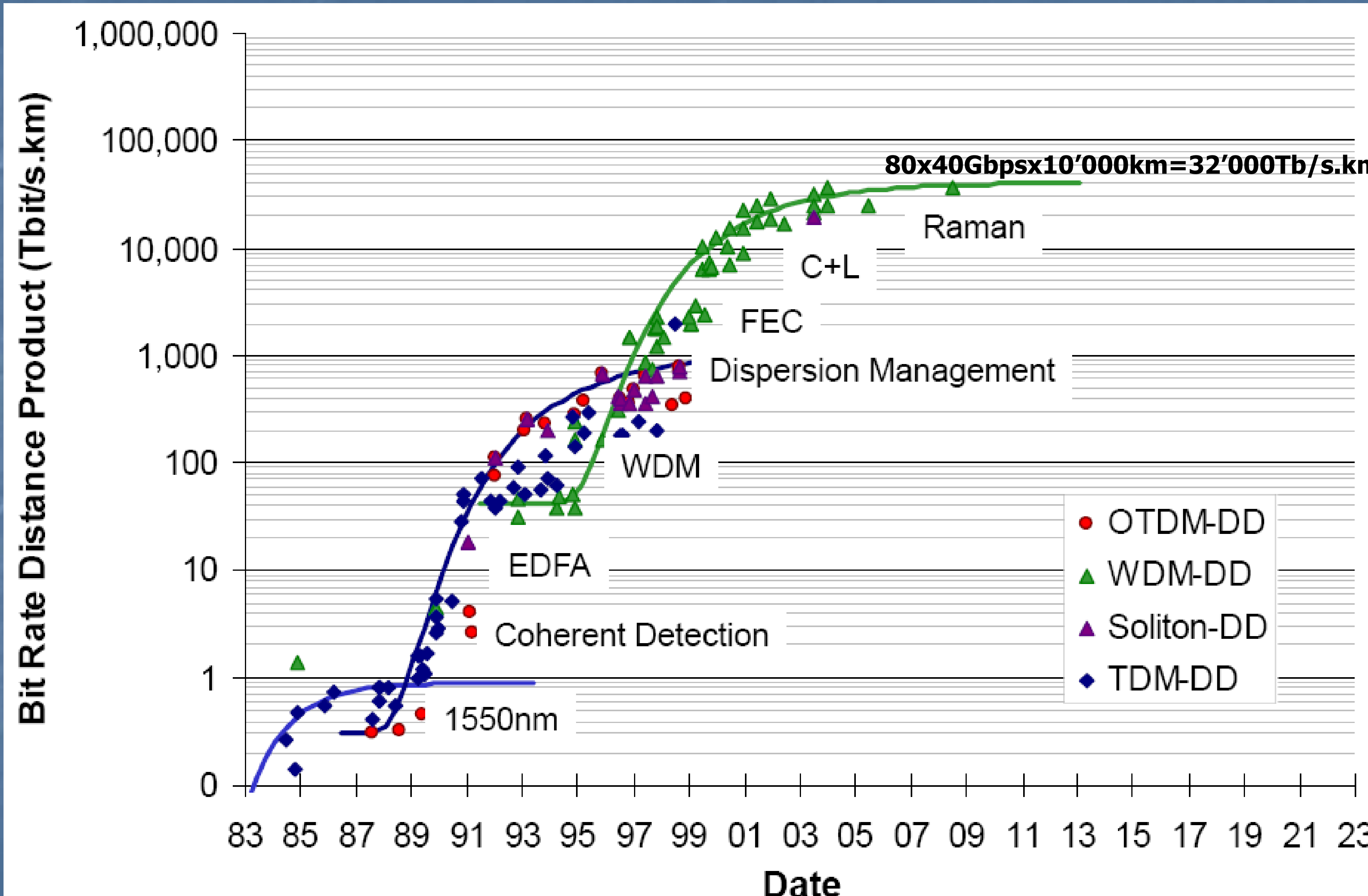


Technology: Capacity

- Context
- Technology
  - Networks
  - Hardware Toolbox
  - Modulation Formats
  - Capacity
  - Standards
- HEP Specifics



Capacity=Bit Rate * Distance

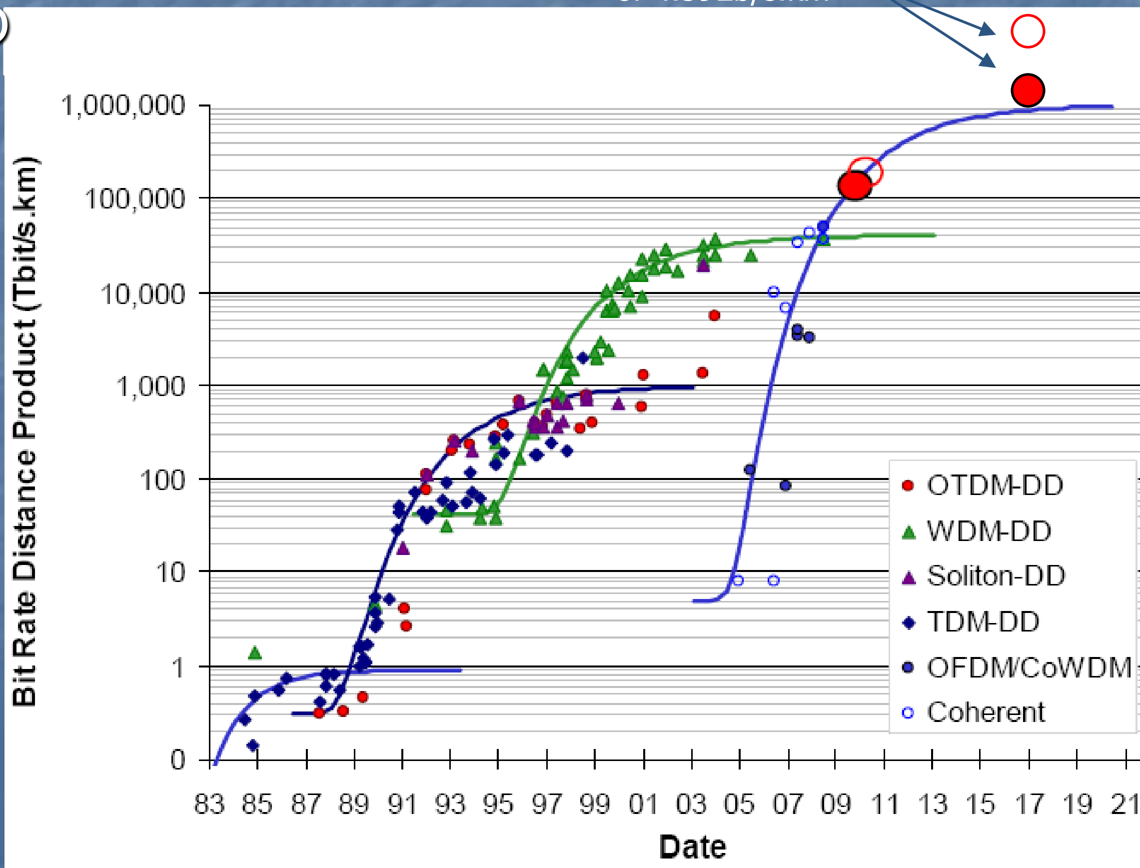


Capacity increase is possible with advanced modulation techniques

- QAM and Coherent detection
- Polarization multiplexing
- High speed DSP, D/A and A/D

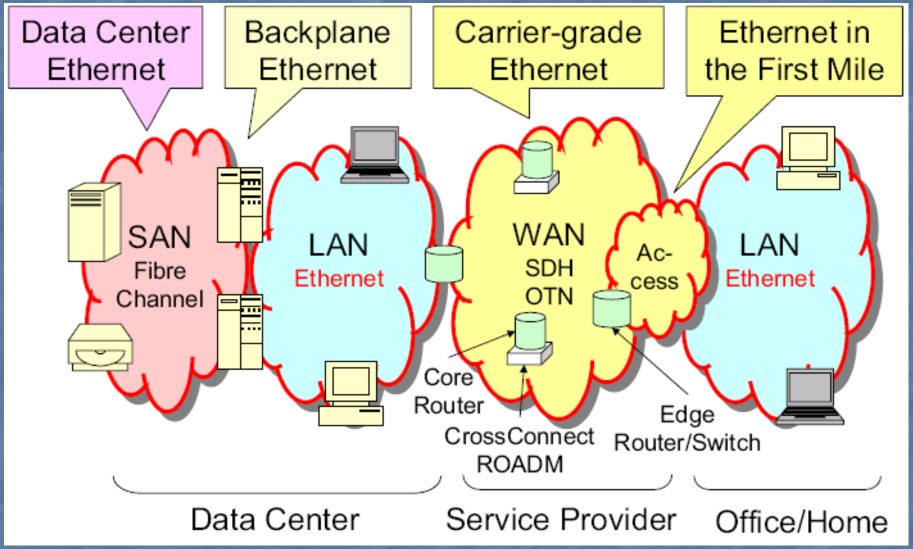
- And to extend the limits:
  - Amplifier waveband extension
  - Multi-core fiber
  - In-line electrical processing
  - …

Turukhin et al (TE subcom), 2017, demonstrated 105.1Tb/s transmission in a 12-core fiber over 14,352km using a power-efficient 8D-APSK modulation format and 82 wavelength channels. Also demonstrated a potential capacity of 4.59Eb/s.km



Technology: Standards

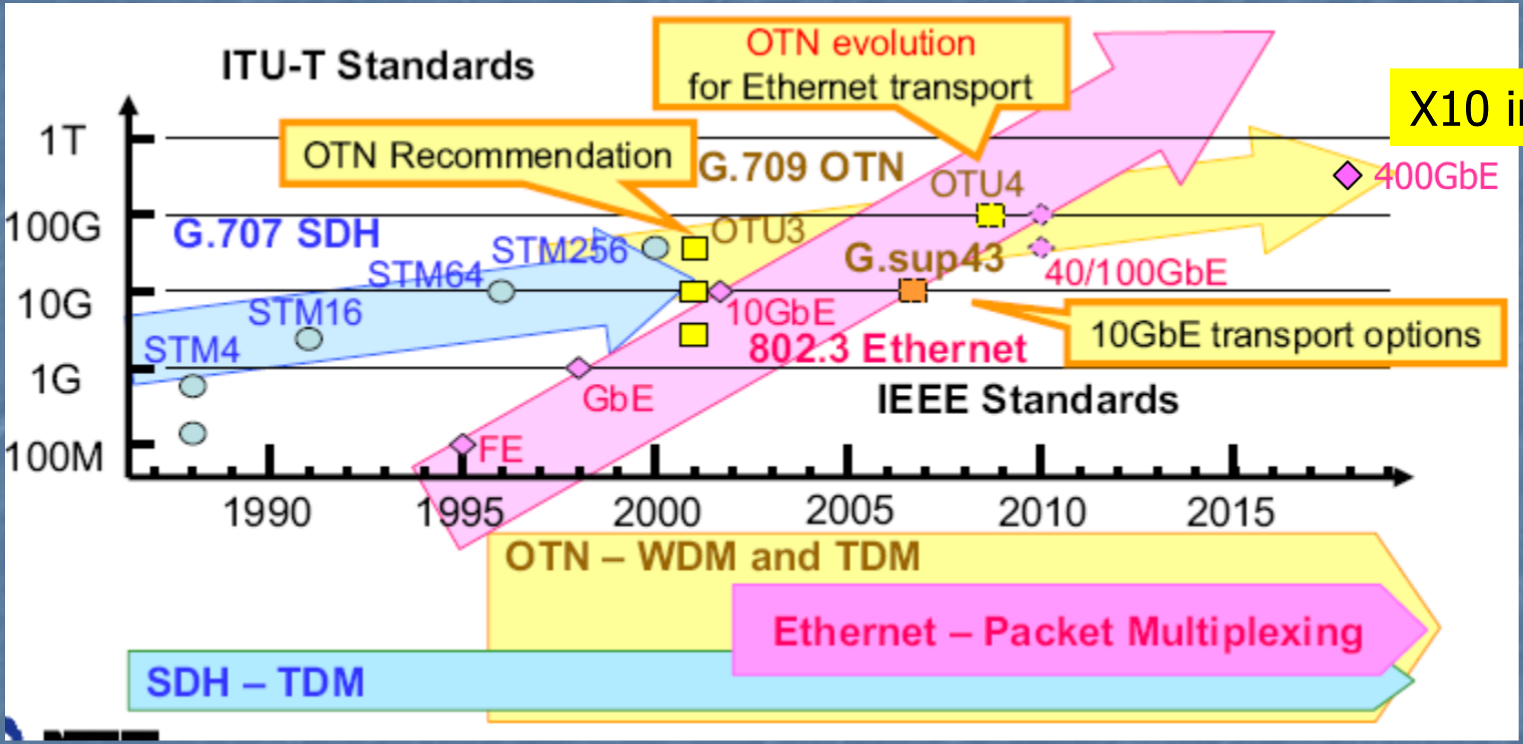
- Context
- Technology
  - Networks
  - Hardware Toolbox
  - Modulation Formats
  - Capacity
  - Standards
- HEP Specifics



Bit Rates vs Standards

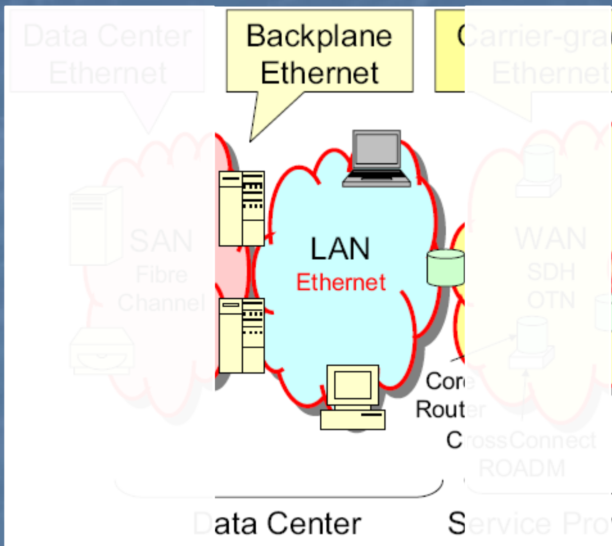
X10 in 4 yrs

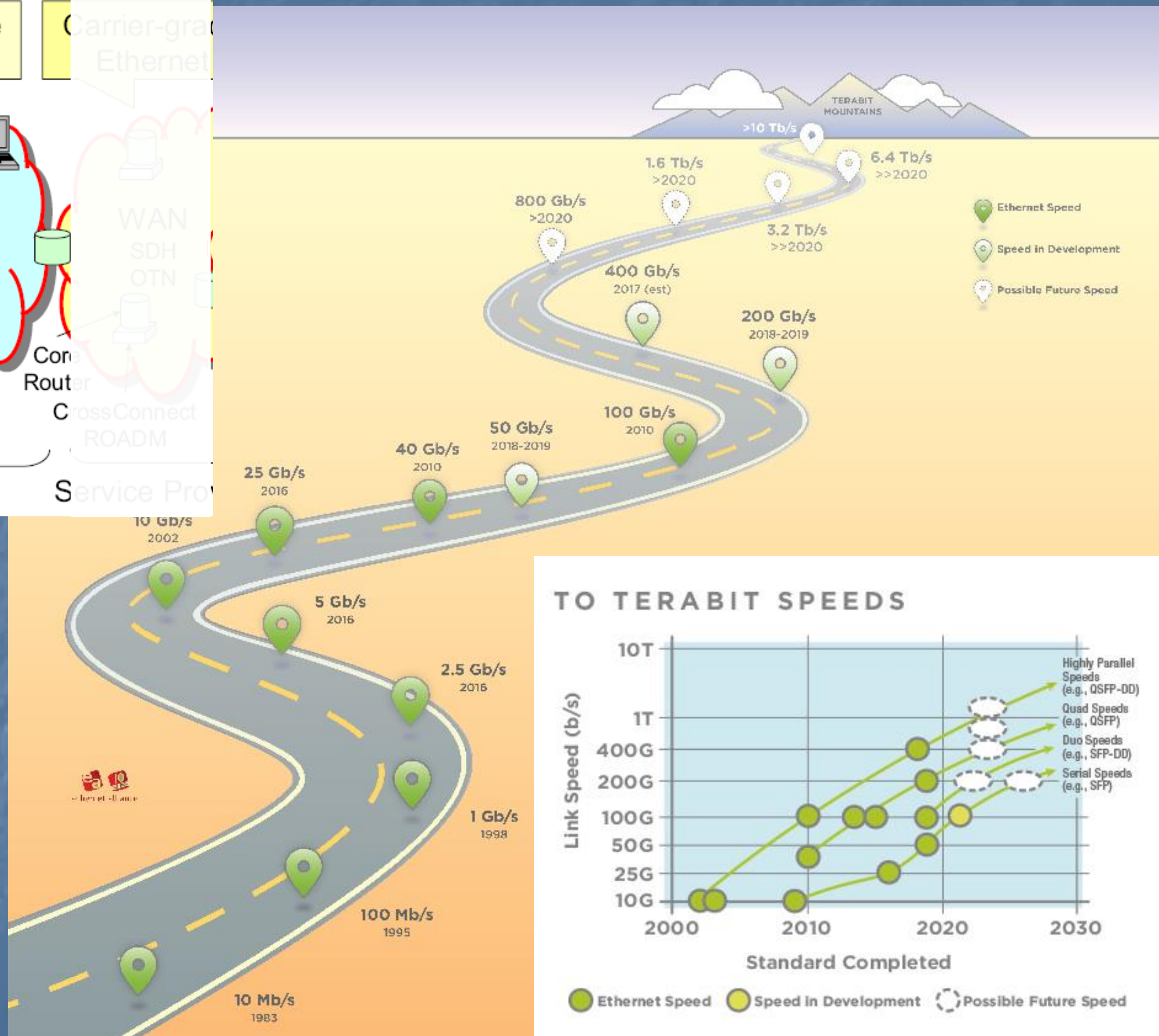
X10 in >10 yrs



IEEE802.3ba Ethernet Roadmap

https://ethernetalliance.org/the-2018-ethernet-roadmap/





Ethernet Interfaces and Nomenclature

	Electrical Interface	Backplane	Twinax Cable	Twisted Pair (1 Pair)	Twisted Pair (4 Pair)	MMF	500m PSM4	2km SMF	10km SMF	40km SMF	80km SMF
10BASE-		T1S?		T1S/T1L							
100BASE-				T1							
1000BASE-				T1	T						
2.5GBASE-		KX		T1S?	T						
5GBASE-		KR		T1S?	T						
10GBASE-				T1S?	T						
25GBASE-	25GAUI	KR	CR/CR-S		T	SR			LR	ER	
40GBASE-	XLAUI	KR4	CR4		T	SR4/eSR4	PSM4	FR	LR4	ER4	
50GBASE-	LAUI-2/50GAUI-2 50GAUI-1	KR	CR			SR		FR	LR	ER	
100GBASE-	CAUI/10 CAUI-4/100GAUI-4 100GAUI-2 100GAUI-1	KR4 KR2 KR1	CR10 CR4 CR2 CR1			SR10 SR4 SR2	PSM4 DR	10X10 CWDM4 CLR4 100G-FR	LR4 4WDM-10 100G-LR	ER4 4WDM-40 ?	?
200GBASE-	200GAUI-4 200GAUI-2	KR4 KR2	CR4 CR2			SR4	DR4	FR4	LR4	?	?
400GBASE-	400GAUI-16 400GAUI-8 400GAUI-4	KR4	CR4			SR16	DR4	FR8 400G-FR4	LR8 ?	?	?

Gray Text = IEEE Standard Red Text = In Standardization Green Text = In Study Group
Blue Text = Non-IEEE standard but complies to IEEE electrical interfaces

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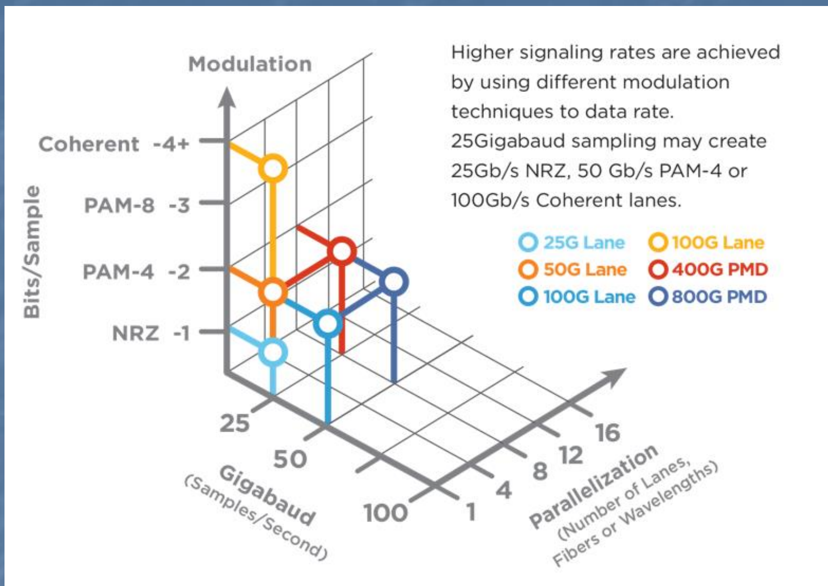
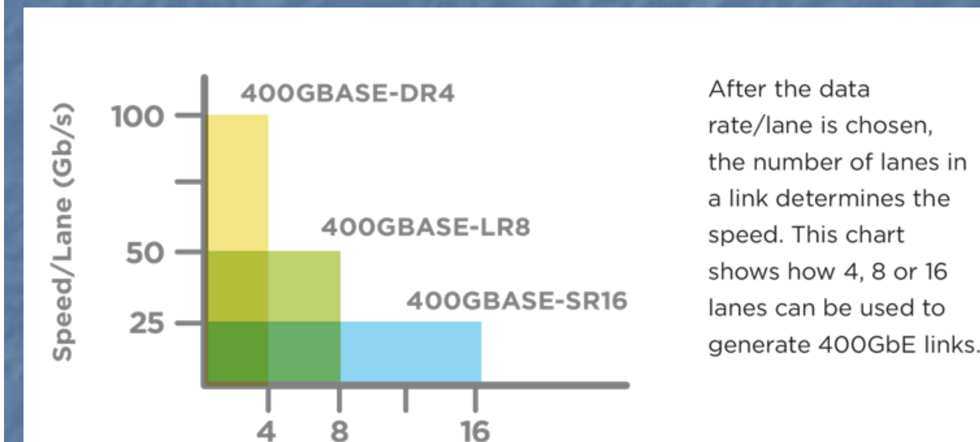
Physical layer	40 Gigabit Ethernet	100 Gigabit Ethernet
Backplane	n.a.	100GBASE-KP4
Improved Backplane	40GBASE-KR4	100GBASE-KR4
7 m over twinax copper cable	40GBASE-CR4	100GBASE-CR10 100GBASE-CR4
30 m over "Cat.8" twisted pair	40GBASE-T	
100 m over OM3 MMF	40GBASE-SR4	100GBASE-SR10
125 m over OM4 MMF[84]		100GBASE-SR4
2 km over SMF, serial	40GBASE-FR	100GBASE-CWDM4[87]
10 km over SMF	40GBASE-LR4	100GBASE-LR4
40 km over SMF	40GBASE-ER4	100GBASE-ER4

Beyond 40/100GbE





100GBASE-	CAUI/10 CAUI-4/100GAUI-4 100GAUI-2 100GAUI-1	KR4 KR2 KR1	CR10 CR4 CR2 CR1			SR10 SR4 SR2	PSM4 DR	10X10 CWDM4 CLR4 100G-FR	LR4 4WDM-10 100G-LR	ER4 4WDM-40 ?	?
200GBASE-	200GAUI-4 200GAUI-2	KR4 KR2	CR4 CR2			SR4	DR4	FR4	LR4	?	?
400GBASE-	400GAUI-16 400GAUI-8 400GAUI-4	KR4	CR4			SR16	DR4	FR8 400G-FR4	LR8 ?	?	?

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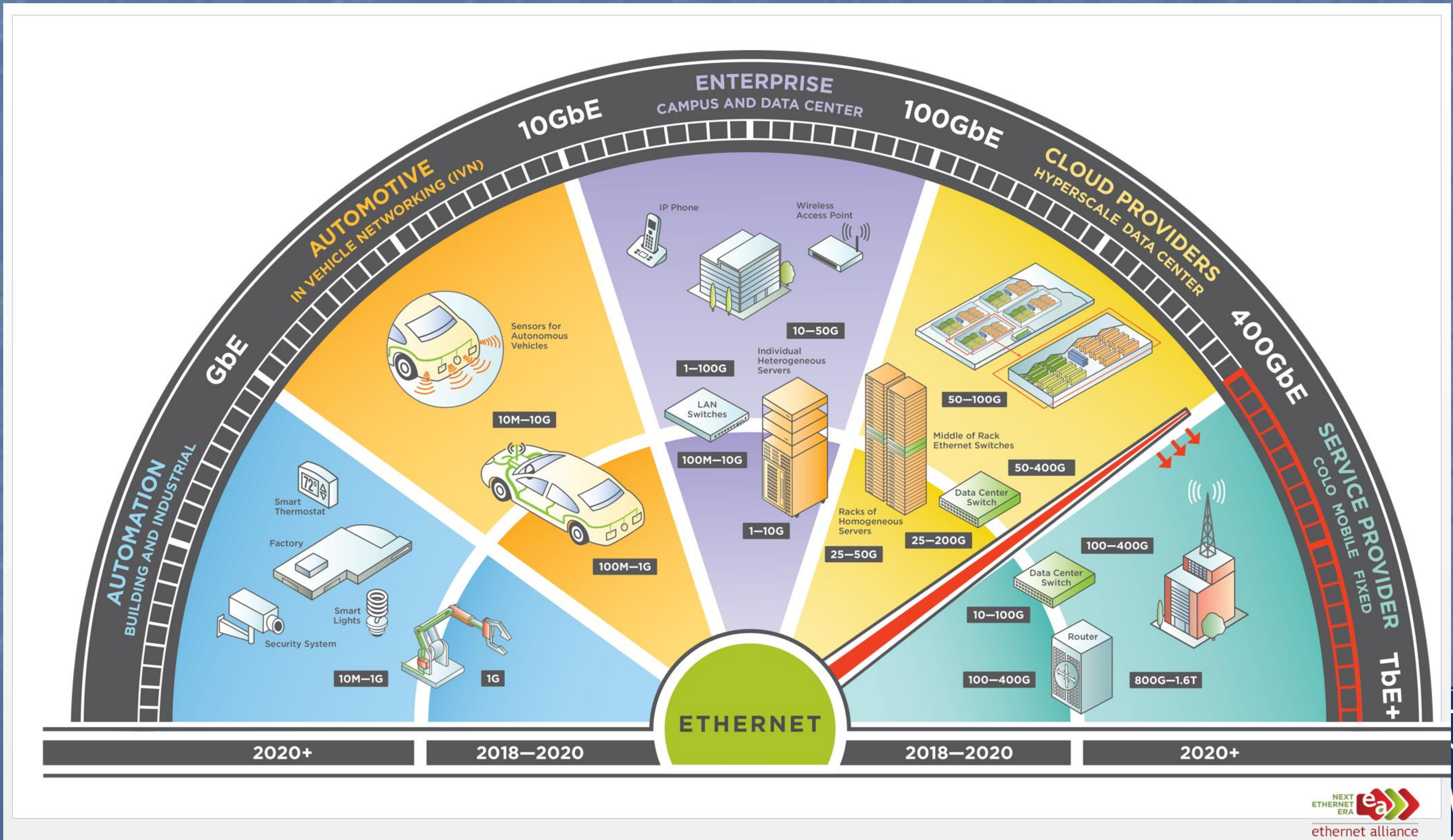
Outlook



ENTERPRISE
CAMPUS AND DATA CENTER
10GbE
100GbE
AUTOMOTIVE
IN VEHICLE NETWORKING (IVN)
CLOUD PROVIDERS
HYPERSCALE DATA CENTER
GbE
400GbE
AUTOMATION
BUILDING AND INDUSTRIAL
SERVICE PROVIDER
COLO MOBILE FIXED
TbE+
IP Phone
Wireless Access Point
10–50G
Individual Heterogeneous Servers
1–100G
LAN Switches
100M–10G
1–10G
Sensors for Autonomous Vehicles
10M–10G
100M–1G
50–100G
Middle of Rack Ethernet Switches
50-400G
Data Center Switch
Racks of Homogeneous Servers
25–200G
25–50G
100–400G
Data Center Switch
10–100G
Router
100–400G
800G–1.6T
Smart Thermostat
Factory
Smart Lights
Security System
10M–1G
1G
ETHERNET
2020+
2018–2020
2018–2020
2020+
NEXT ETHERNET ERA
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