Agilent Customer Training Seminar

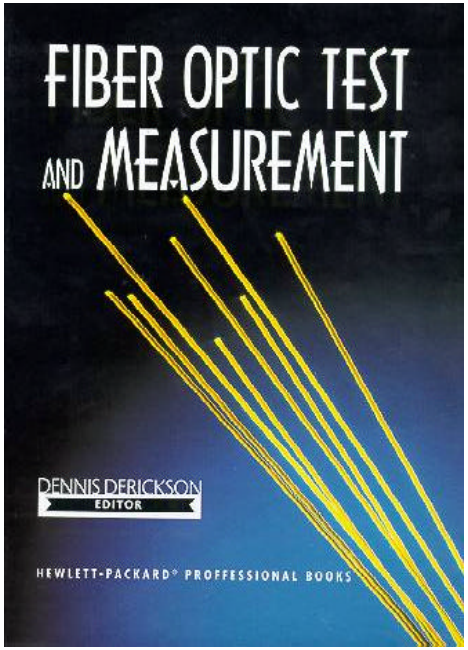
Elements of Lightwave Technology

Table of Content

Lightwave Test Literature

Agilent employees have published many white papers, product notes, and application notes discussing most lightwave measurements.

See handouts for a list of literature references.



Thank You

For Choosing

Agilent Technologies

As Your Partner In

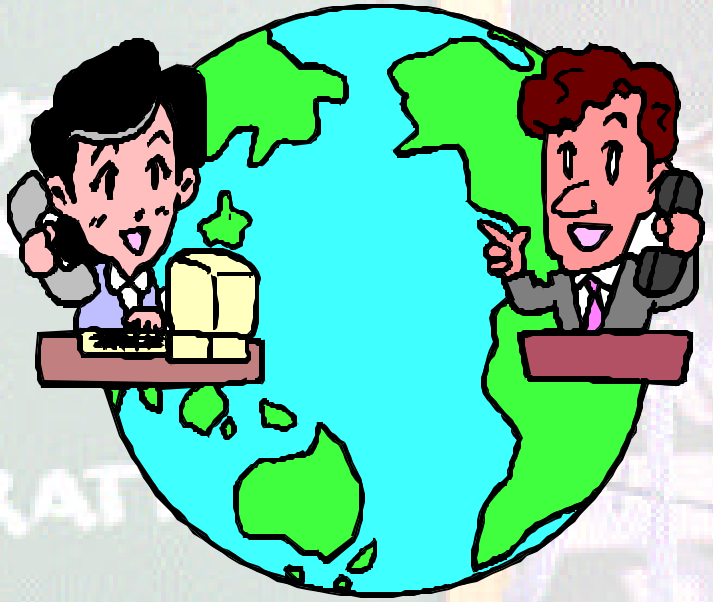
Lightwave & High Speed Digital

Transmission Test

Agilent Technologies
Innovating the HP Way

Lightwave Division

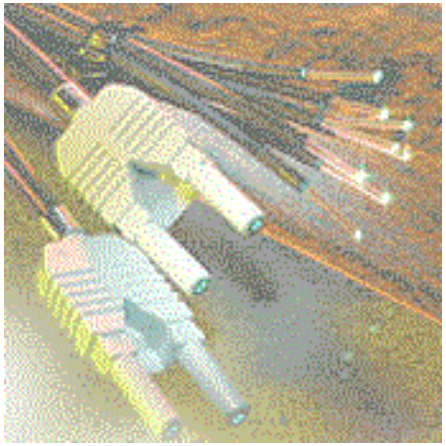
LW Technology



Introduction

What is lightwave technology?

- Lightwave technology uses light as the primary medium to ***carry information***.
- The light often is guided through optical fibers ***(fiberoptic technology).***
- Most applications use ***invisible (infrared) light***.



(HP)

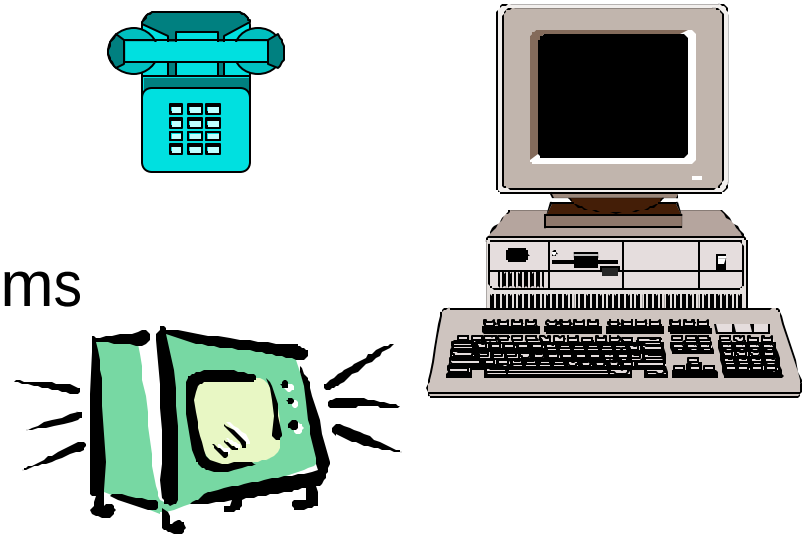
Why lightwave technology?

- ***Most cost-effective way*** to move ***huge amounts of information*** (voice, data) ***quickly and reliably***.
- Light is ***insensitive*** to electrical ***interference***.
- Fiberoptic cables have ***less weight*** **and consume *less space*** than equivalent electrical links.

(HP)

Use Of Lightwave Technology

- Majority applications:
  - Telephone networks
  - Data communication systems
  - Cable TV distribution
- Niche applications:
  - Optical sensors
  - Medical equipment
  - Displays & signs



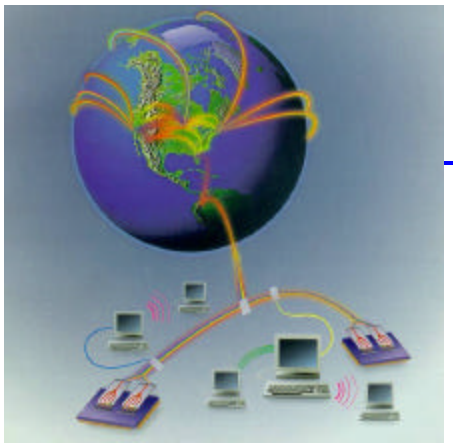
Telephone Networks

- Long distance telecommunication
  - up to 600 km repeater spans, up to 9000 km total link length
  - Most demanding, most expensive
  - *Keywords: submarine, longhaul*

- Access network (1 km - 20 km)
  - Cost driven, less competition
  - *Keywords: local exchange, regional interexchange, MAN, FTTC, FTTH*

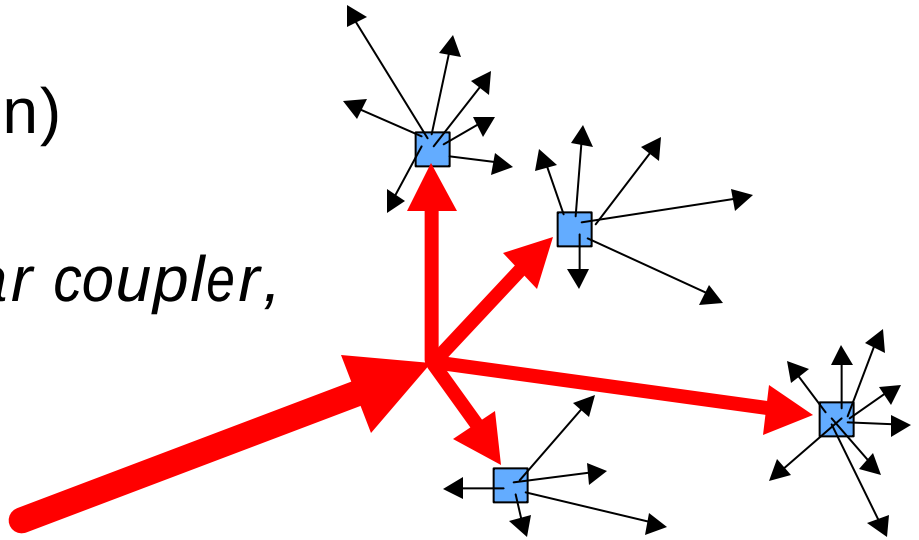
Other Networks

- Data communication (1 m - 500 m)
  - As cheap as it can get
  - *Keywords: premises network, LAN, backbone, FDDI, Gigabit-Ethernet, Fibre Channel*

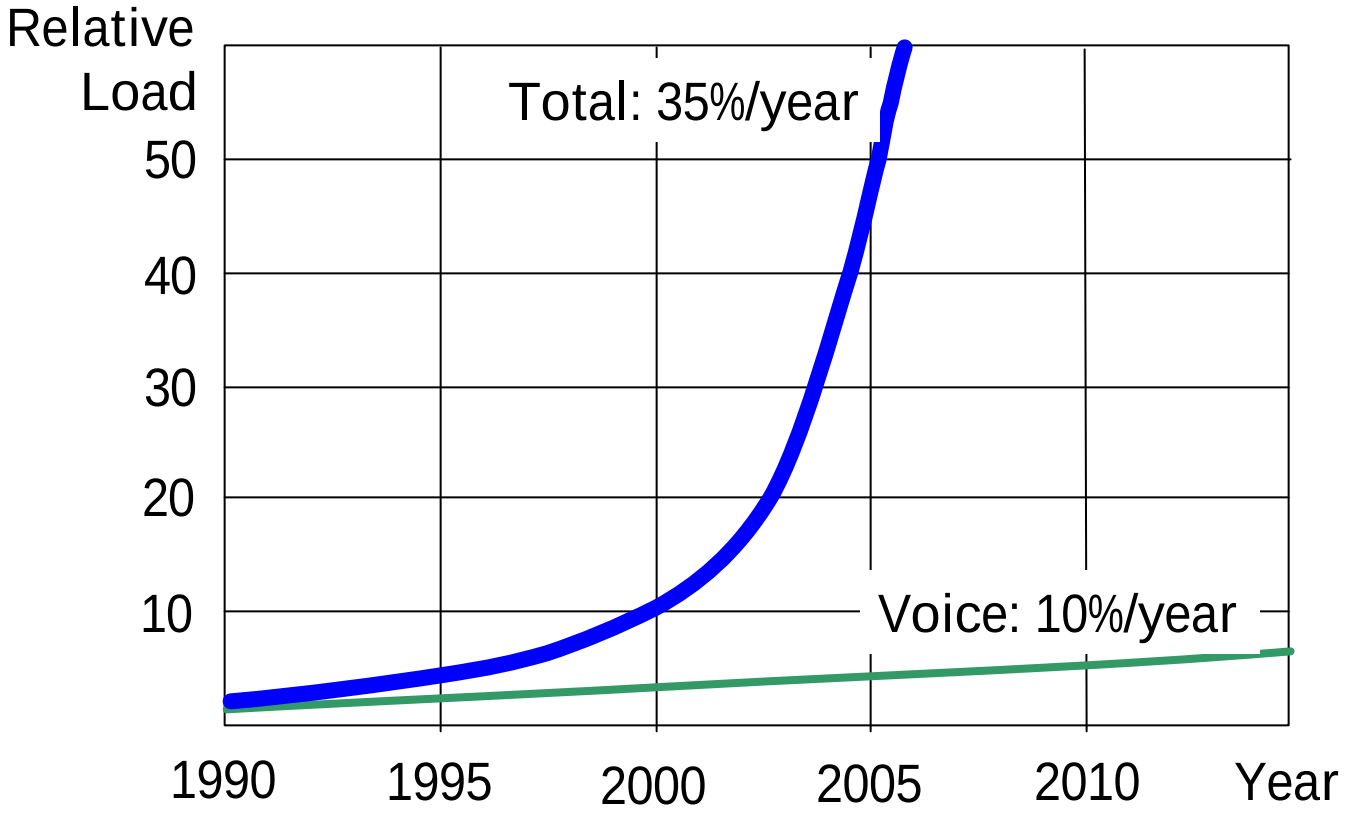


HP Journal 12/97

- Cable TV (urban distribution)
  - Analog network
  - *Keywords: head end, star coupler, subcarrier*

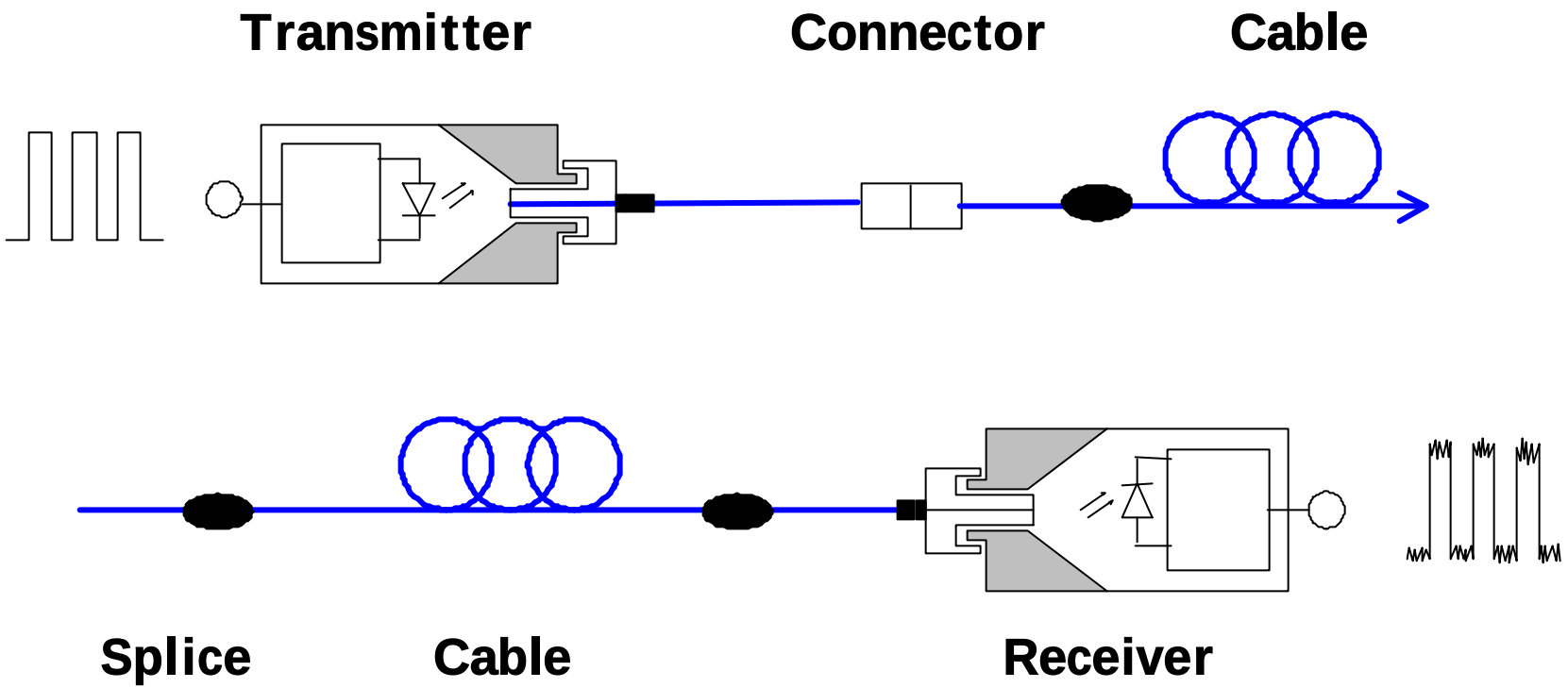


Telecommunication Network Bandwidth Trend

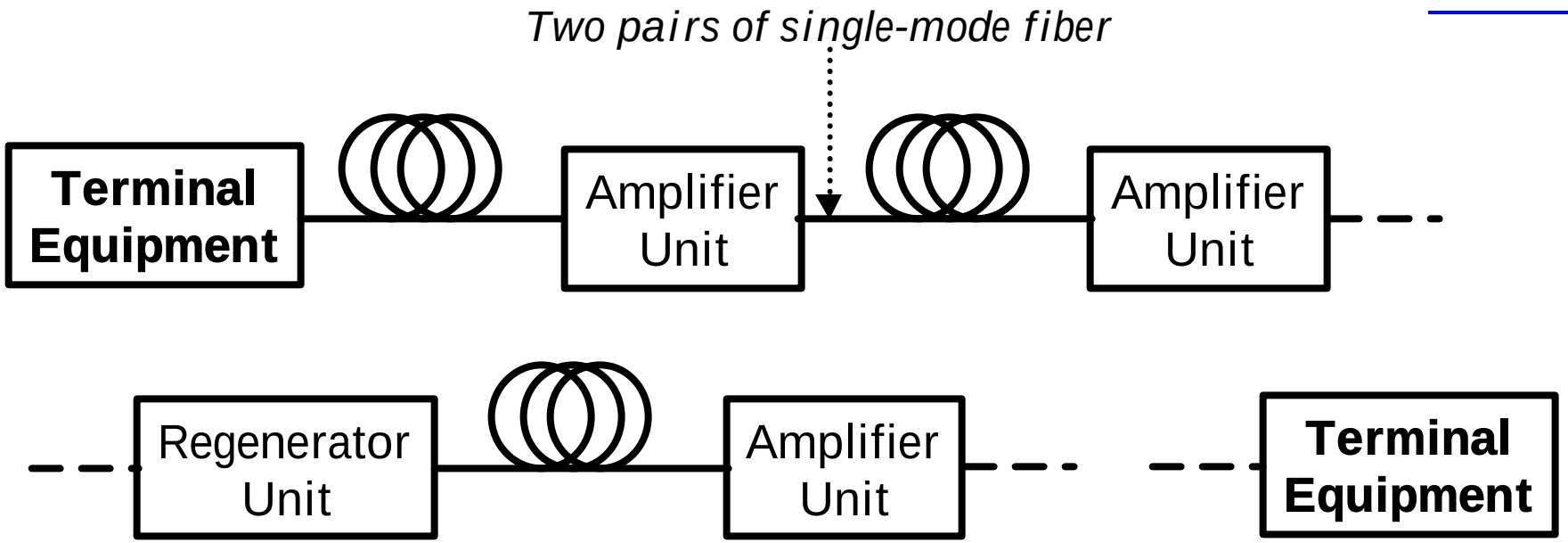


Source:
ElectroniCast Corporation

Basic Link Design

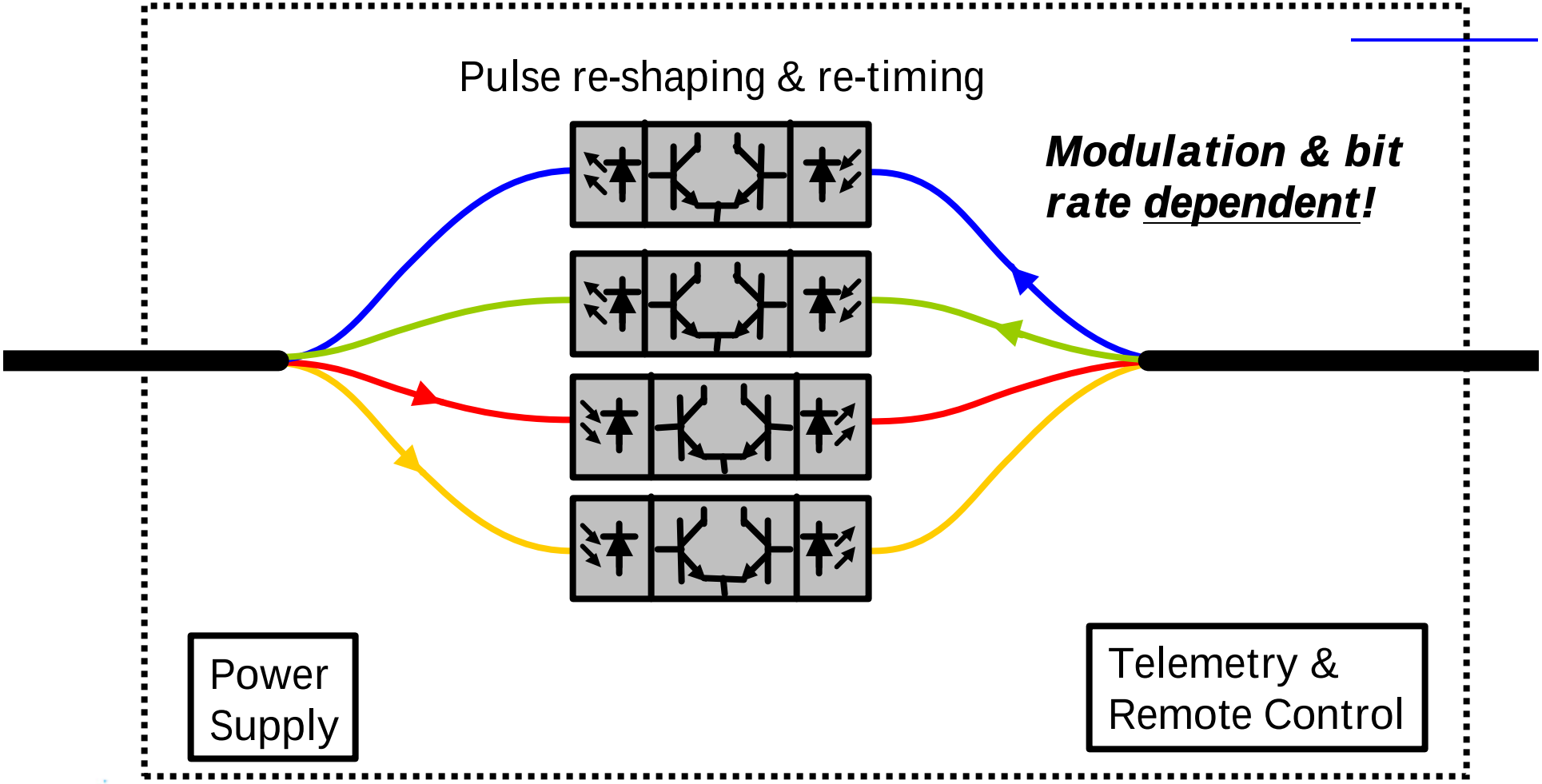


Typical Long-haul System

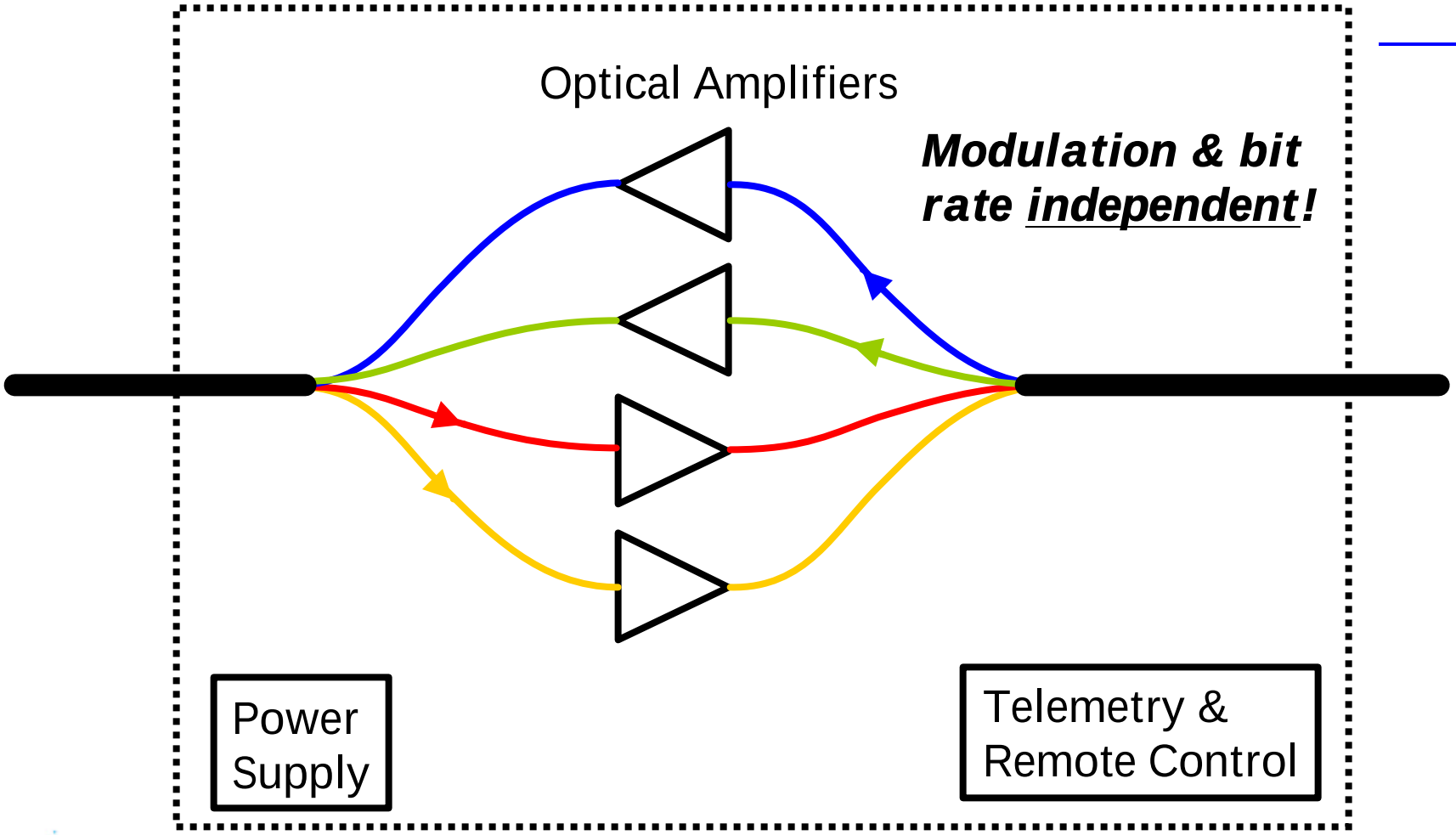


Amplifier spans:	30 to 120 km
Regenerator spans:	50 to 600 km
Terminal spans:	up to 600 km (without regenerators)
	up to 9000 km (with regenerators)

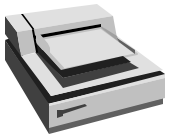
Typical Regenerator Unit



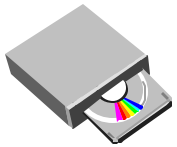
Typical Amplifier Unit



Data Communication Trends



Fibre Channel @2.5 Gbps GigaBit Ethernet @1.25 Gbps



Fast Ethernet @100 Mbps

1994 1996 1998 2000 2002

SCSI/ USB/ PCI@ 66 Mbps

IEEE1394 FireWire@ 400 Mbps

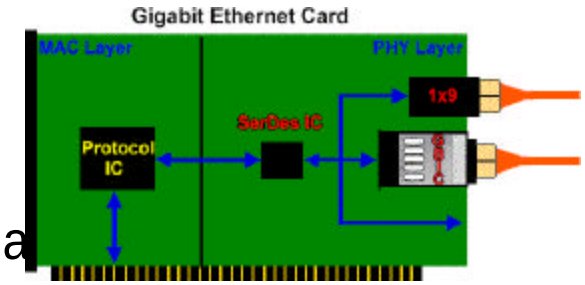
IEEE1394 FireWire@ 1.6 Gbps

IEEE1394 FireWire@ 3.2 Gbps

POLO@ 10 Gbps

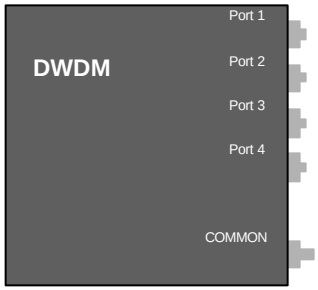
Data Communication Buzzwords

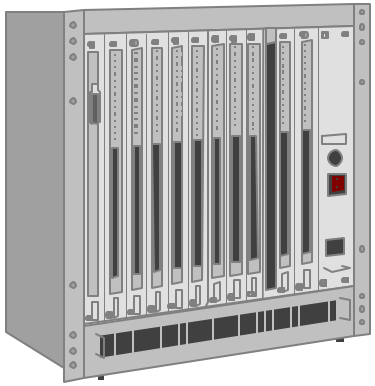
- Wide Area Network (WAN)
  - Nationwide or global data network
  - Often provided or operated by multiple long-distance service providers
- Metropolitan Area network (MAN)
  - Regional or local data network
  - Often owned by a local service provider
- Local Area Network (LAN)
  - Private computer network
  - Often shielded from the outside by firewalls
- Dial-Up Network
  - Connects a PC via modem & telephone to a da



Company Types

- Component Manufacturers
  - *Lasers/LEDs, photodetectors, couplers, multiplexers, isolators, fibers, connectors*
- Subsystem Manufacturers
  - *Transmitters, receivers, amplifiers (EDFA), repeaters*
- System Manufacturers
  - *Point-to-point, SONET/SDH, WDM*
- Installers & Service Providers
  - *Link signature, fault location*





Review Questions

1. What advantages does the lightwave technology offer?

2. Who is using fiberoptics extensively?

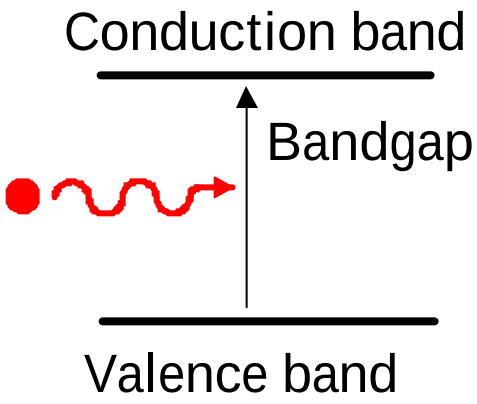
3. What modulation (analog or digital) is used in the telephone network?

LW Technology

Physical Basics

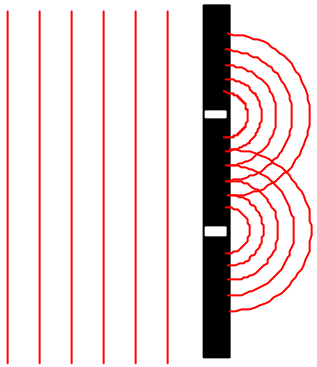
The Carrier - Light

Particles



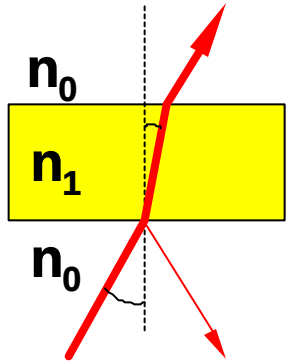
Absorption
Emission

Waves



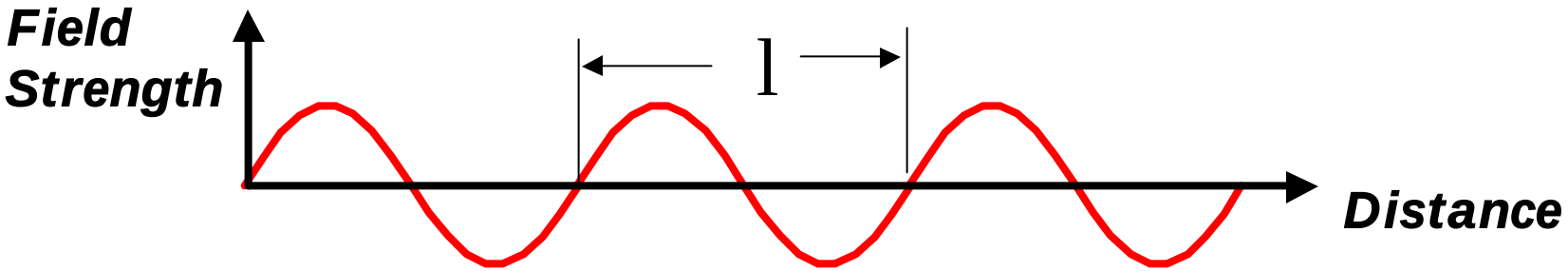
Interference

Rays



Refraction
Reflection

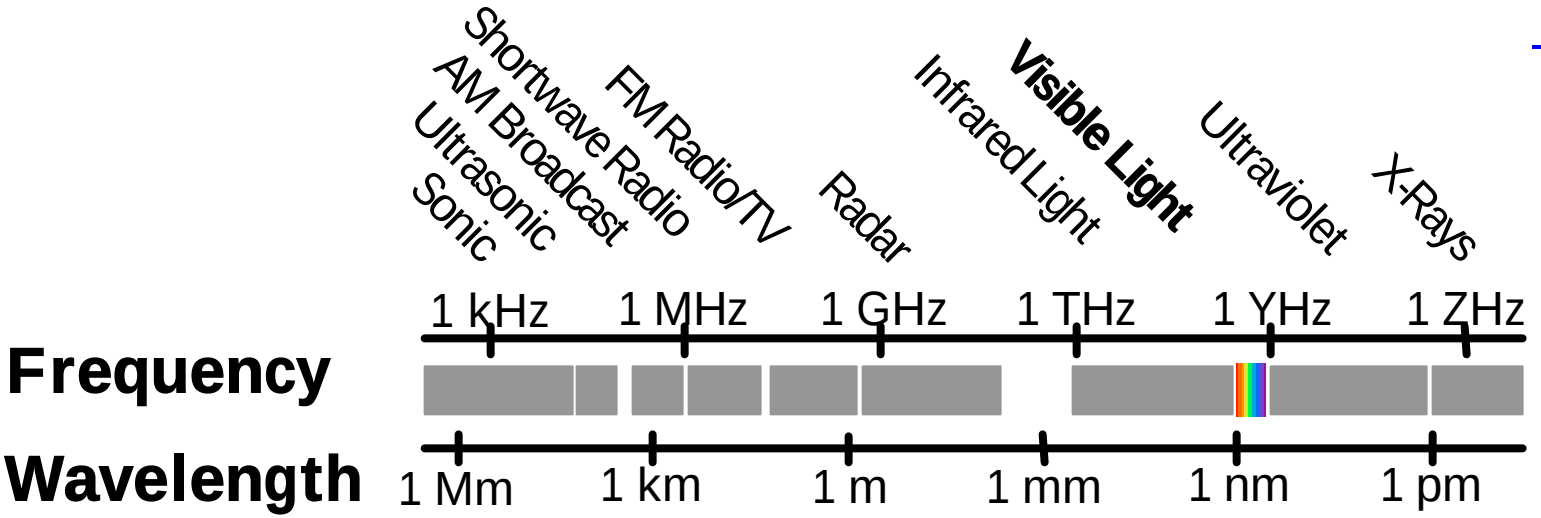
Light Properties - Wavelength



Wavelength λ: **distance to complete one sine wave**

1000 pm (picometer)	*= 1* ***nm (nanometer)***	*1000 μm*	*= 1 mm (millimeter)*
1000 nm (nanometer)	*= 1* ***μm (micrometer)***	*1000 mm*	*= 1 m (meter) (~40 inches)*

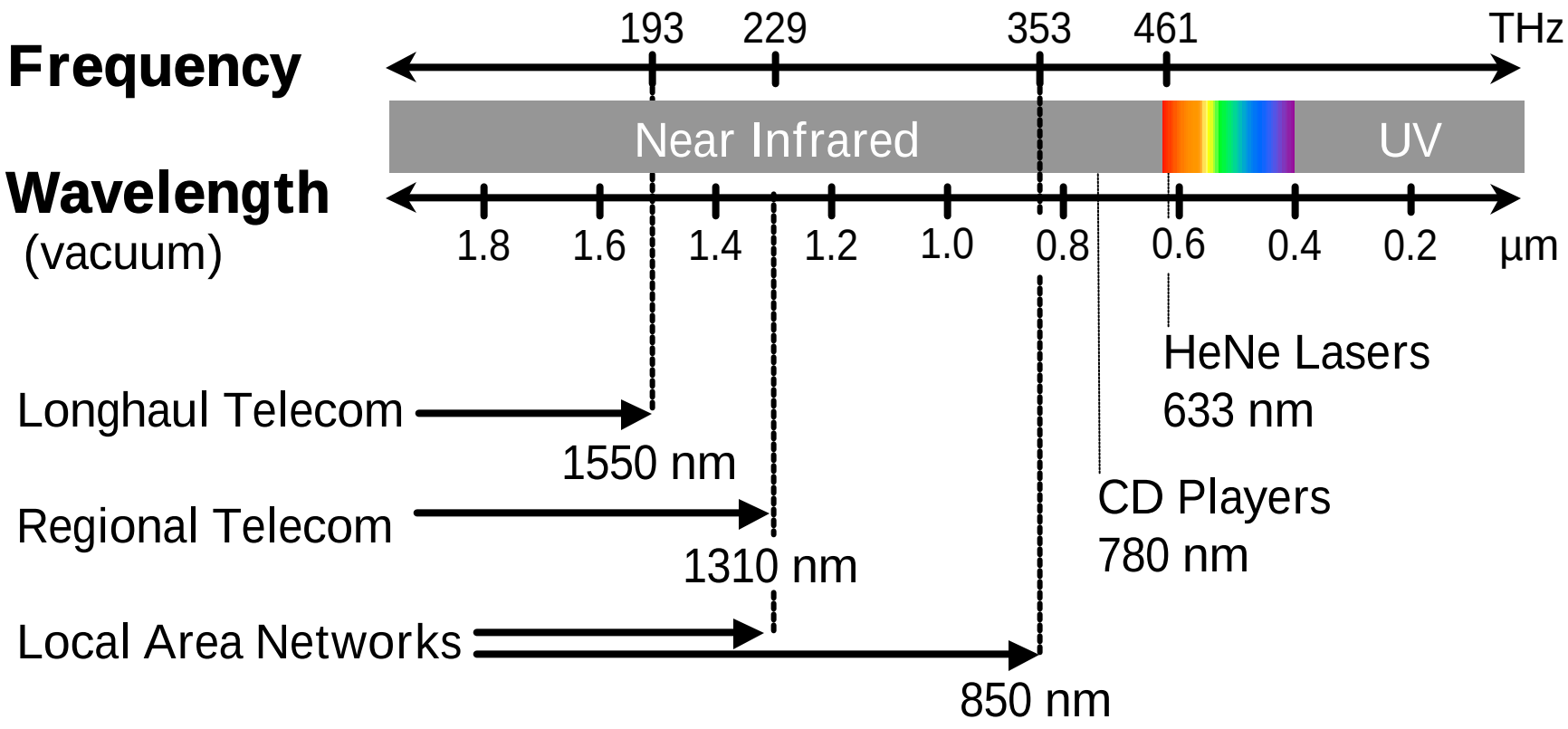
Electromagnetic Spectrum



c = f • l • n

c: Speed of light (2.9979 m/µs)
f: Frequency
λ: Wavelength
n: Refractive index
(vacuum: 1.0000; standard air: 1.0003; silica fiber: 1.44 to 1.48)

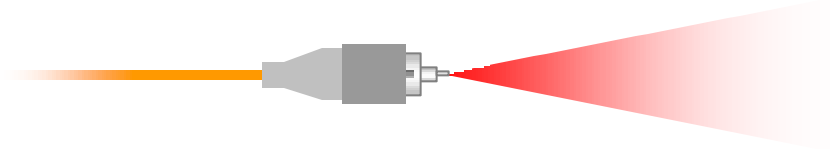
LW Transmission Bands



Optical Power

- Power (P):
  - *Transmitter: typ. -6 to +17 dBm (0.25 to 50 mW)*
  - *Receiver: typ. -3 to -35 dBm (500 down to 0.3 µW)*
  - *Optical Amplifier: typ. +3 to +20 dBm (2 to 100 mW)*

- Laser safety
  - International standard: IEC 825-1
  - United States (FDA): 21 CFR 1040.10
  - Both standards consider **class I** safe under reasonable forseeable conditions of operation (e.g., without using optical instruments, such as lenses or microscopes)



Laser Power Limits Of Class I
(for test equipment applications)

21 CFR 1040.10		
Wavelength	Fiber / NA	Limit
850 nm	MM / 0.15	2.8 mW
1060 to 1400 nm	MM / 0.15	4.9 mW
	SM / 0.10	1.9 mW
1400 to 2500 nm	SM / 0.10	7.84

(1984)

IEC 825-1 (EN 60825-1)		
Wavelength	Fiber / NA	Limit
850 nm	MM / 0.15	0.44 mW
1200 to 1400 nm	MM / 0.15	8.9 mW
	SM / 0.10	8.9 mW
1400 to 4000 nm	SM / 0.10	10 mW

(11/1993)

The Logarithmic Scale

dB = $10 \cdot \log_{10} (P_1 / P_0)$

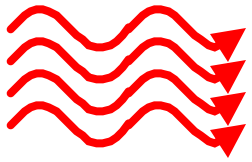
0 dB	= 1
+ 0.1 dB	= 1.023 (+2.3%)
+ 3 dB	= 2
+ 5 dB	= 3
+ 10 dB	= 10
-3 dB	= 0.5
-10 dB	= 0.1
-20 dB	= 0.01
-30 dB	= 0.001

dBm = $10 \cdot \log_{10} (P / 1\ mW)$

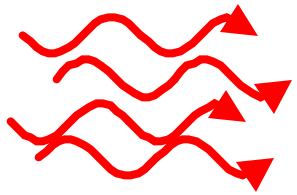
0 dBm	= 1 mW
3 dBm	= 2 mW
5 dBm	= 3 mW
10 dBm	= 10 mW
20 dBm	= 100 mW
-3 dBm	= 0.5 mW
-10 dBm	= 100 μW
-30 dBm	= 1 μW
-60 dBm	= 1 nW

Coherence

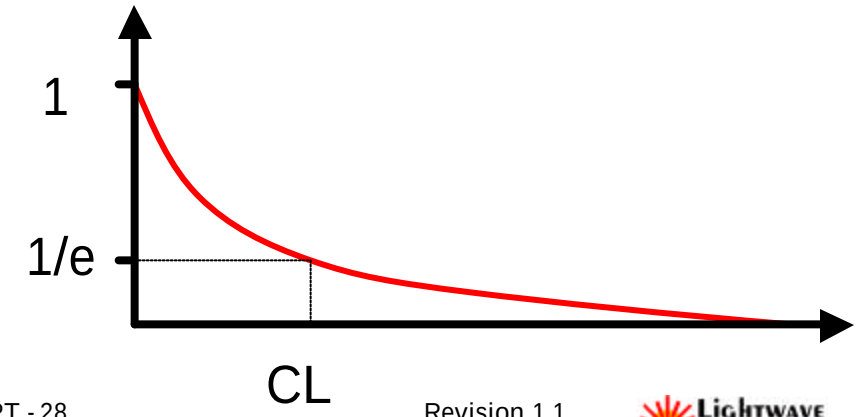
- Coherent light
  Photons have fixed phase relationship (laser light)



- Incoherent light
  Photons with random phase (sun, light bulb)

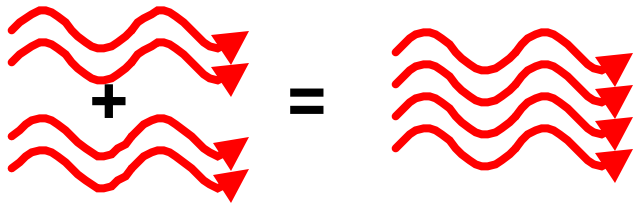


- Coherence length (CL)
  Average distance over which photons lose their phase relationship

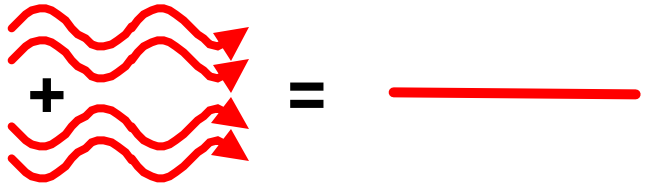


Interference

- Incoherent light adds up *optical power*
- Coherent light adds *electromagnetic fields*
- Zero phase shift:
  constructive interference



- 180º phase shift:
  destructive interference



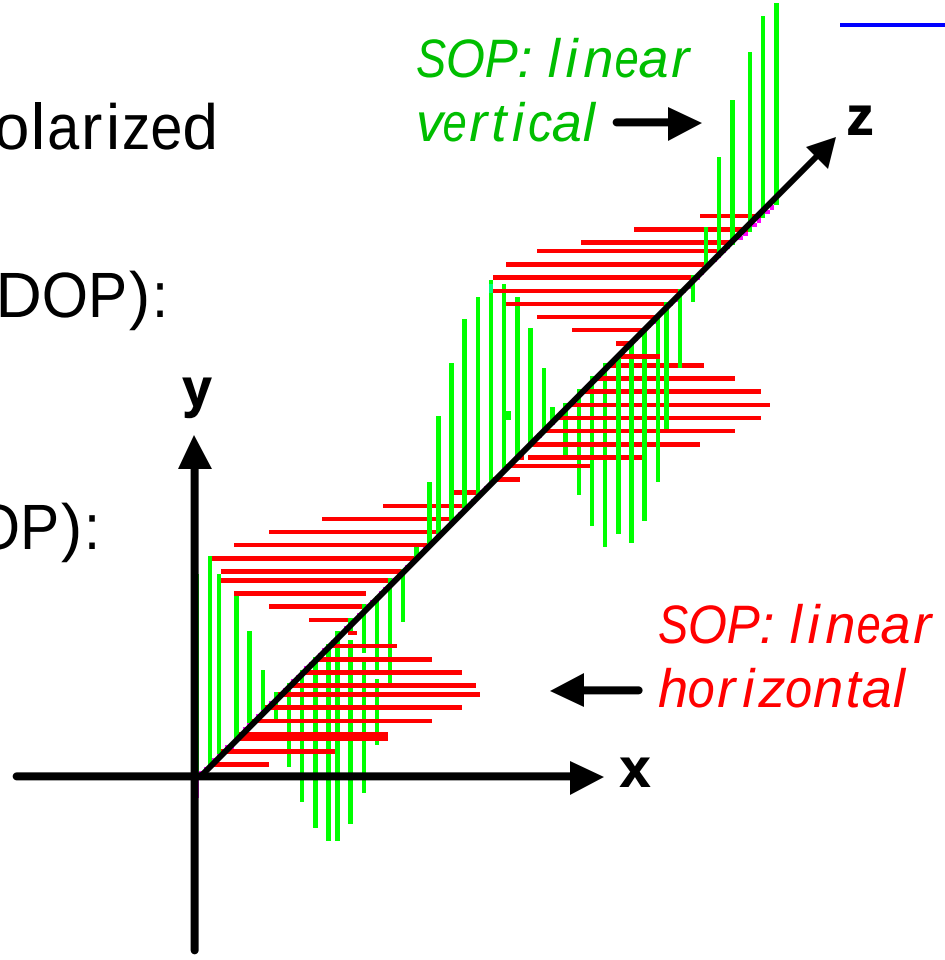
Reflections

- Reflections: root cause for many problems
  Return loss definition:

$$RL = 10 * \log \frac{P_{incident}}{P_{reflected}}$$

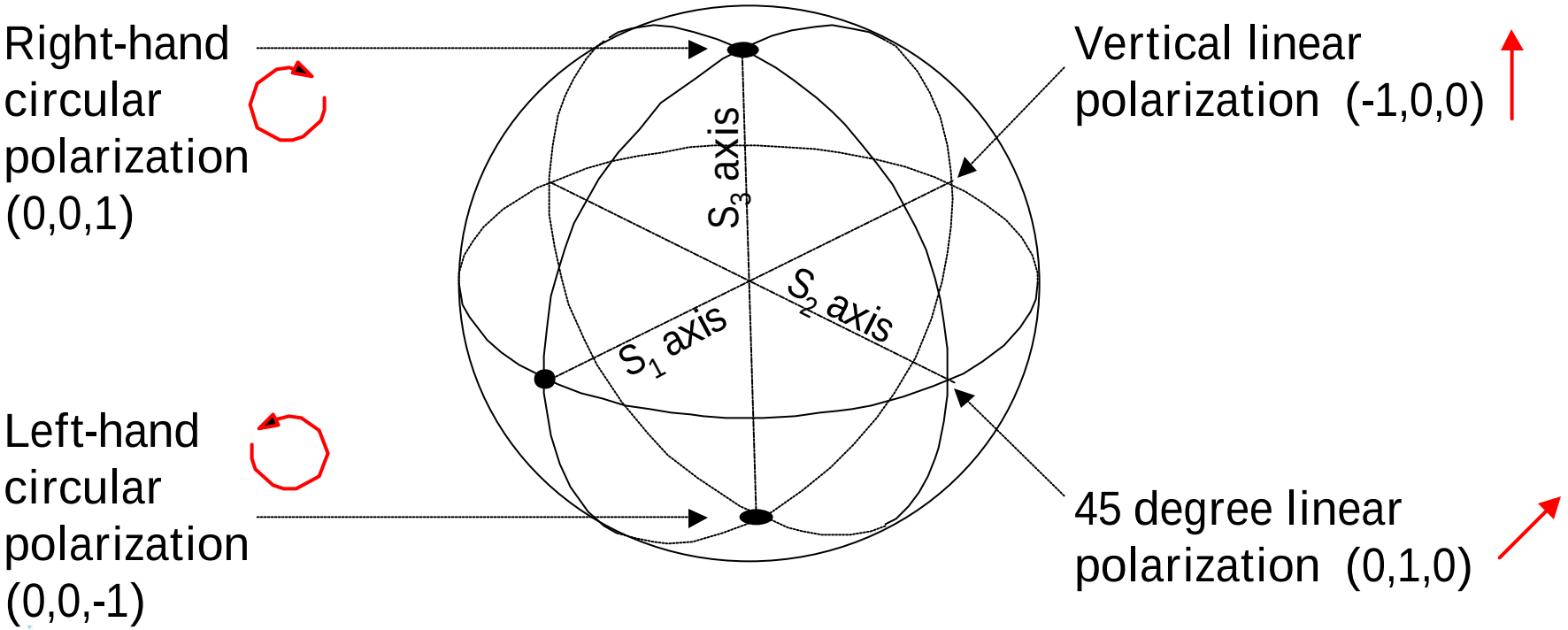
Polarization

- Most lasers are highly polarized
- Degree of polarization (DOP):
  $DOP = P_{polarized} / P_{total}$
- State of polarization (SOP):
  describes the orientation and rotation of the polarized light



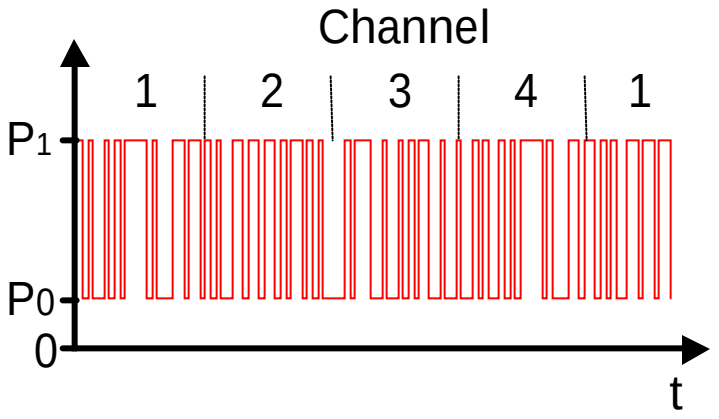
Poincaré Sphere

Graphical representation of ***state*** of polarization using Stokes parameters (S_1, S_2, S_3)



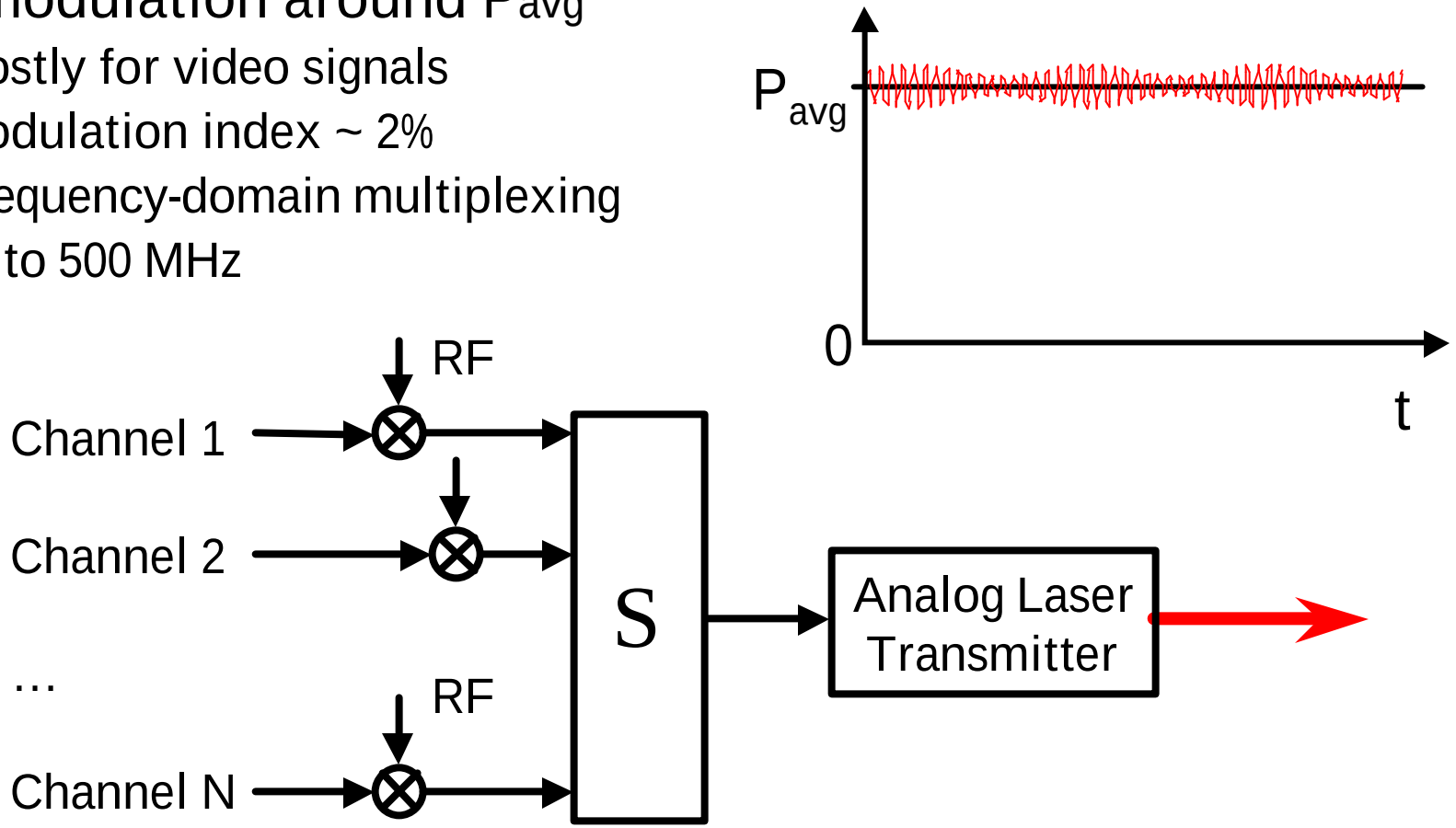
Digital Modulation

- Digital Modulation:
  - Extinction ratio = P1 / P0
  - Time-division multiplexing (TDM)
  - ~1.5 Mb/s to 10 Gb/s
- Bit Error Rate (BER):
  - BER = $N_{incorrect}$ / N_{total}
  - Standards: 1E-9 to 1E-12
  - Lightwave systems: down to 1E-15



Analog Modulation

- AM modulation around P_{avg}
  - Mostly for video signals
  - Modulation index ~ 2%
  - Frequency-domain multiplexing
  - 50 to 500 MHz



Review Questions

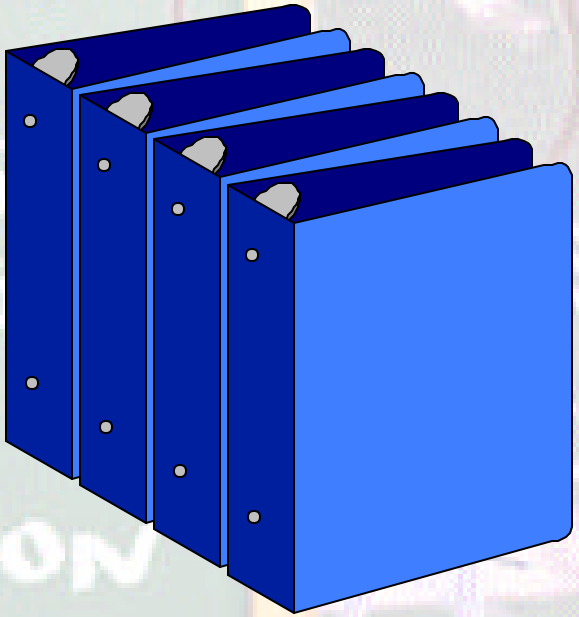
1. What are the three key parameters of light?

2. How much power is +13 dBm? -27 dBm?
   How much loss is 6 dB? 15 dB?

3. What is TDM?

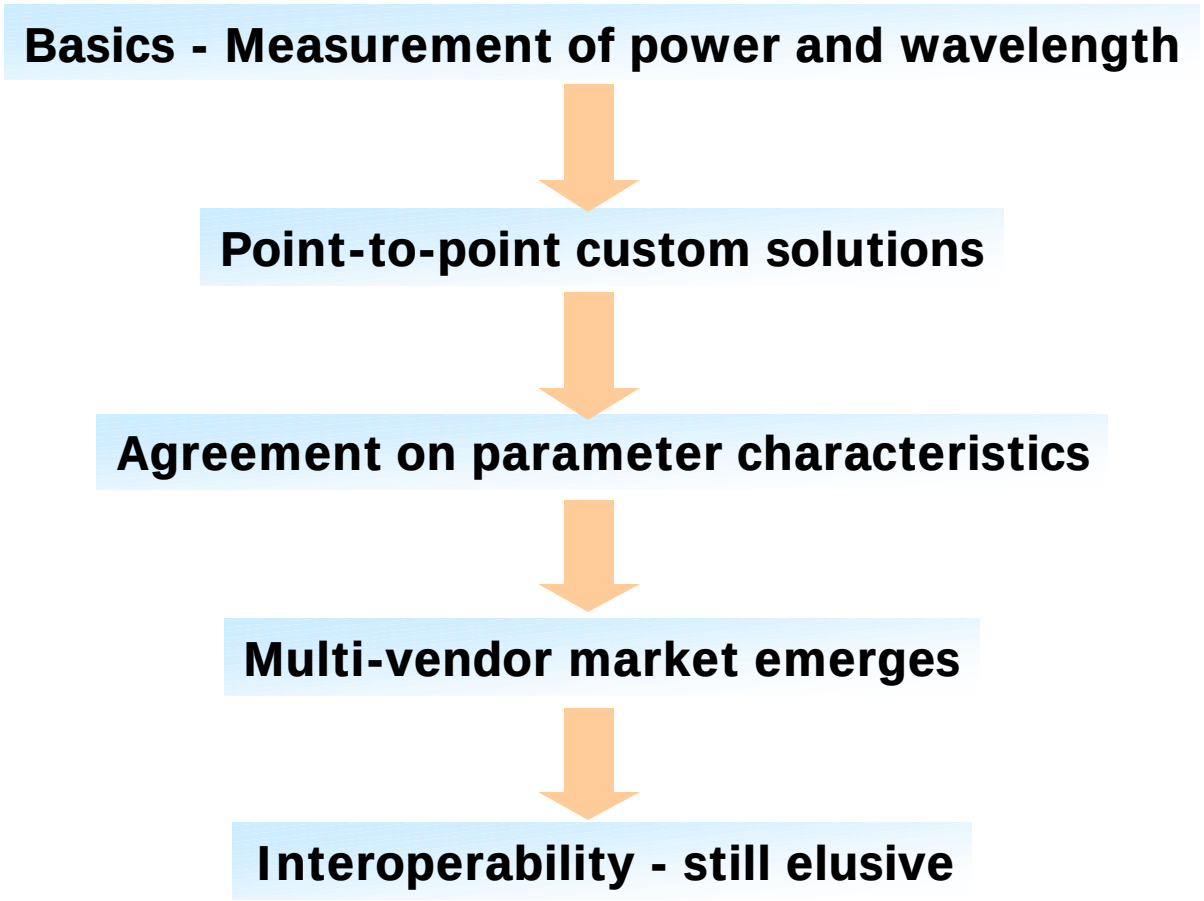
4. Where on the Poincaré sphere is the horizontal linear polarization state?

LW Technology

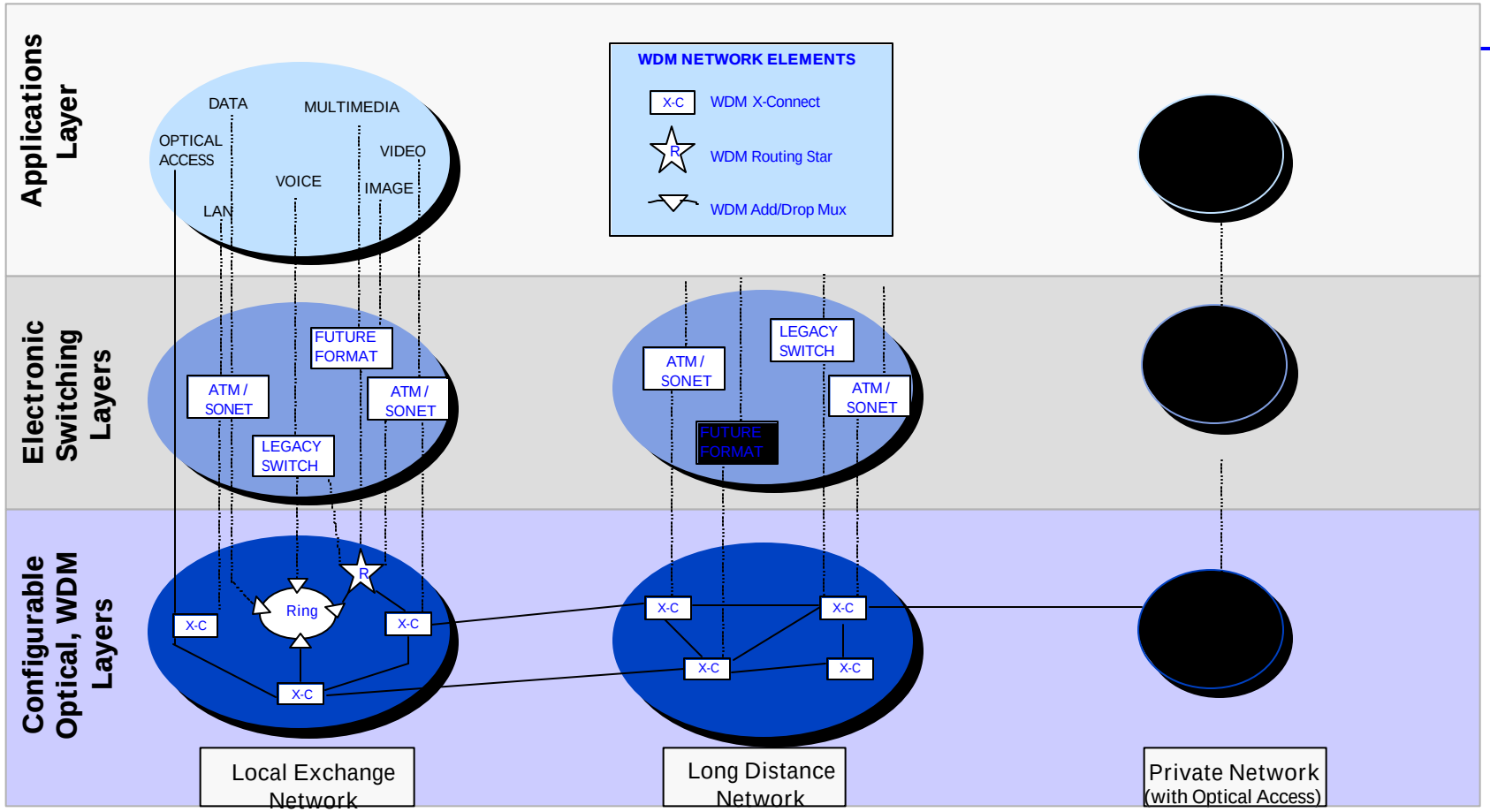


Standards

Lightwave Standards Evolution



Network Model



Key Standards

- Telecom Standards
  - Plesiochronous Digital Hierarchy (PDH)
  - Synchronous Optical Network (SONET) / Synchronous Digital Hierarchy (SDH)
  - Asynchronous Transfer Mode (ATM)
  - Dense Wavelength-Division Multiplexing (DWDM)
- Datacom Standards
  - Ethernet, Fast Ethernet (coax or twisted air cable)
  - Gigabit-Ethernet (IEEE 802.3z)
  - Fiber Distributed Data Interface (FDDI)
  - Fibre Channel (FC-PH)
  - Internet Protocol (IP)

PDH Networks

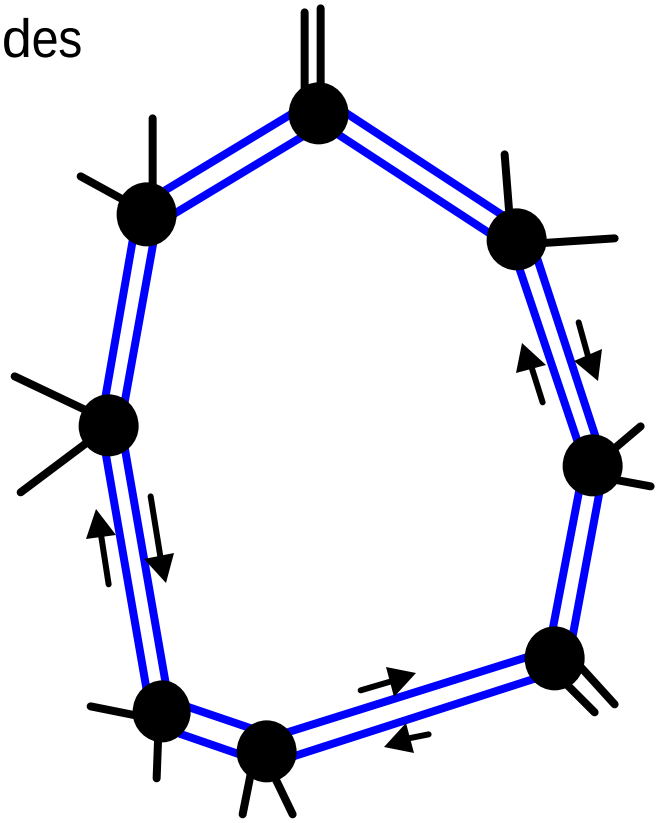
- Developed in the early 1970's
  - Still many systems in place, especially for low speed traffic
- Multiplexes digital voice circuits (64 kb/s)
  - North America: DS1 (1.5 Mb/s) to DS4 (139 Mb/s)
    Europe: E1 (2 Mb/s) to E4 (139 Mb/s)
    Japan: 2 to 98 Mb/s
- Drawbacks
  - Not perfectly synchronized: extra bits needed
  - Difficult to add/drop low speed stream from high-speed stream
  - No standard on line interfaces & coding (interoperability!)
  - Seconds to minutes to restoration time after a failure

SONET / SDH

- THE standard for new telecom networks:
  - North America: SONET version
  - International: SDH version
  - Optimized for voice traffic
  - Virtual container technology can carry many different traffic types & speeds
- Definitions include:
  - Optical requirements
  - Modulation and BER
  - Functional layer (e.g., frames)
  - Protection and restoration
  - Network management

Typical Ring Structures

- Two pairs of fibers between nodes
  - One fiber for each direction between nodes
  - One restoration fiber for each direction
- Network cut (single fault)
  - Traffic rerouted in opposite direction
  - Restoration within 0.5 sec
  - 100% protection!
- Nodes types
  - Add/drop multiplexers (ADM)
  - Digital cross-connects (DTE)

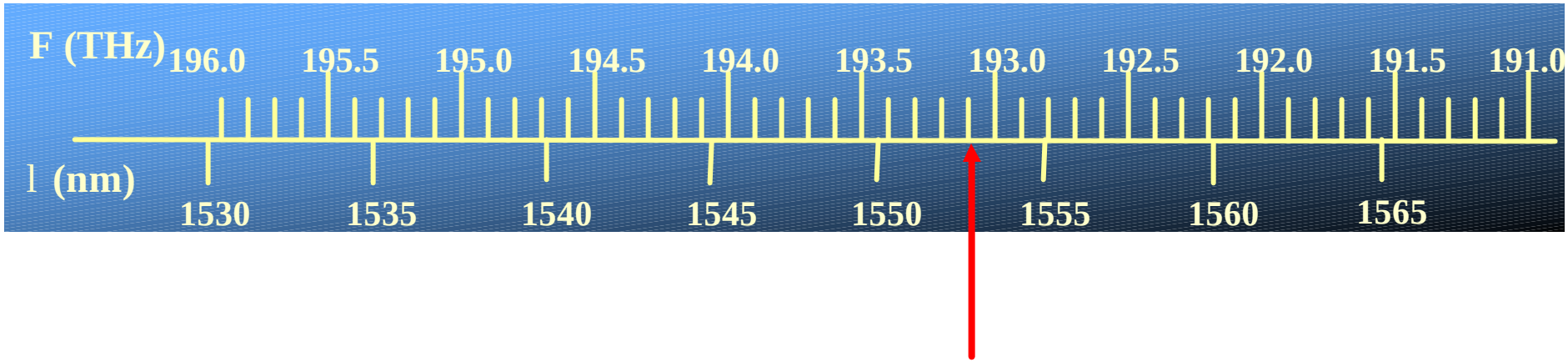


DWDM Standards

- ITU Draft Recommendation G.692:
  "Optical Interfaces for Multichannel Systems with Optical Amplifiers"

  - Specifies interfaces for the purpose of providing future transverse compatibility among such systems.
  - Defines the wavelength grid for multichannel systems.
  - Currently on hold pending resolution of intellectual property issues.
  - Large backlog of proposed changes/additions.

The Frequency Grid From G.692



- Channels anchored at a 193.1-THz reference
- 100-GHz spacing with no defined lower or upper bound.

The U.S. (TIA) will formally propose a change to 50-GHz spacing.

Asynchronous Transfer Mode (ATM)

- High performance data transfer standard
  - Uniform cell: 5 header bytes, 48 data bytes
  - Simple and efficient cell switching
  - Optimizes use of available network capacity
- Quality of Service (QoS)
  - Bandwidth and delay guarantees
  - Admission control to satisfy QoS
- Compatibility with installed networks
  - Can run over PDH or SONET/SDH systems

Internet Protocol (IP)

- WAN / MAN / LAN protocol for data
  - Originally designed for data (e-mail, file transfer)
  - Voice & video applications under development
- Layered design
  - Key contribution to widespread deployment
  - Can be easily adapted to new technologies
  - Higher layers can run over other data networks as long as they provide compatible services
- Point-to-Point protocol (PPP)
  - Common data link layer to connect PCs to LANs or to the internet via phone lines (e.g., home PC with modem)

7 - Application
6 - Presentation
5 - Session
4 - Transport
3 - Network
2 - Data link
1 - Physical

Common Transmission Speeds

- **SONET/SDH rates:**
  - OC-3, STM-1: 155.52 Mb/s
  - OC-12, STM-4: 622.08 Mb/s
  - OC-48, STM-16: 2488.32 Mb/s
  - OC-192, STM-64: 9953.28 Mb/s
- **Datacom rates:**
  - FDDI: 125 (100) Mb/s
  - FireWire: 100 - 800 Mb/s
  - Fibre Channel: 266 - 1063 Mb/s
  - Ethernet: 10 or 100 Mb/s
  - G-Ethernet: 1250 Mb/s
- **PDH:**

  North America:
  - *DS1: 1.544 Mb/s*
  - *DS2: 6.312 Mb/s*
  - *DS3: 44.736 Mb/s*
  - *DS4: 139.264 Mb/s*

  Europe:
  - *E1 2.048 Mb/s*
  - *E2: 8.448 Mb/s*
  - *E3: 34.368 Mb/s*
  - *E4: 139.264 Mb/s*

Review Questions

1. Why do most operators like SONET/SDH ?

2. What is the advantage of a layered design?

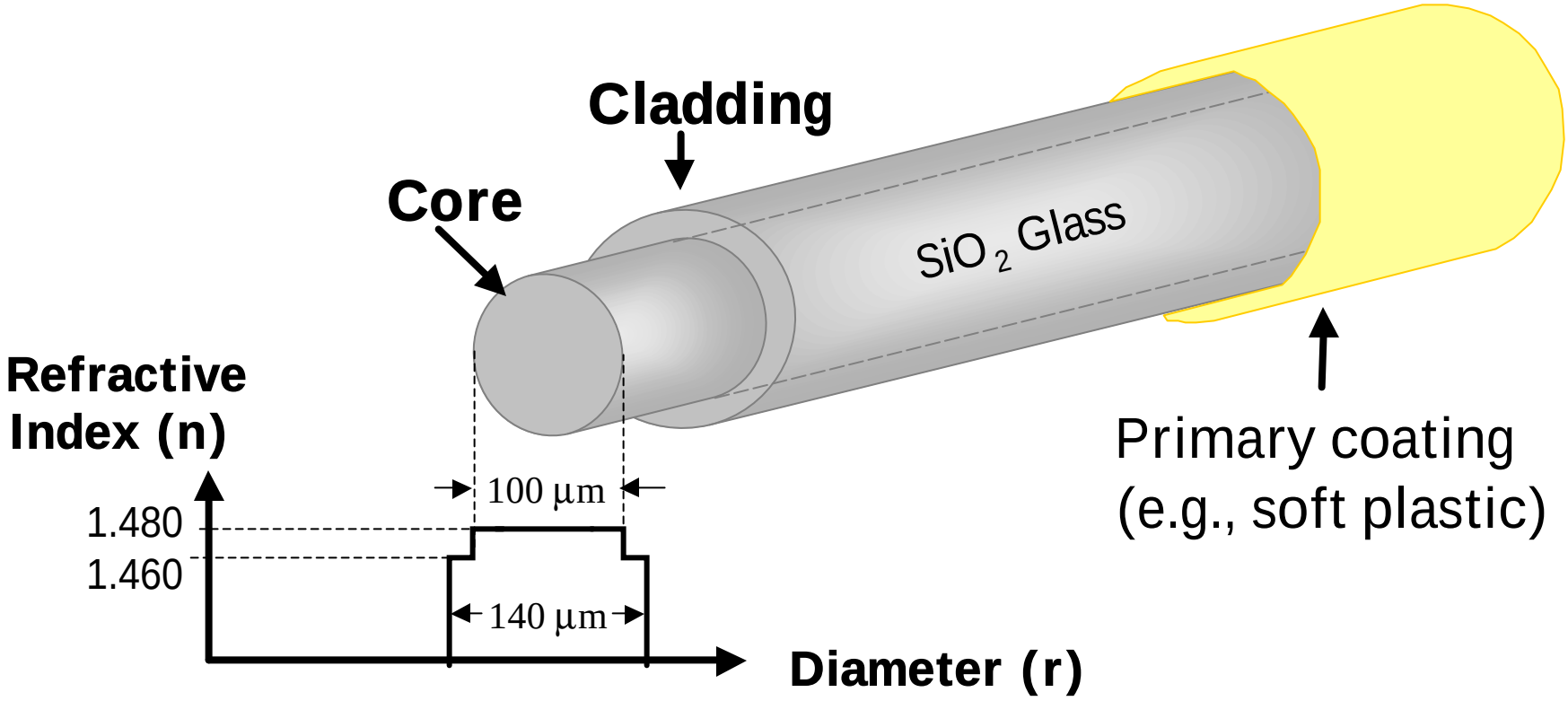
4. What are the key properties of DWDM?

LW Technology

Fibers, Cables, Splices & Connectors

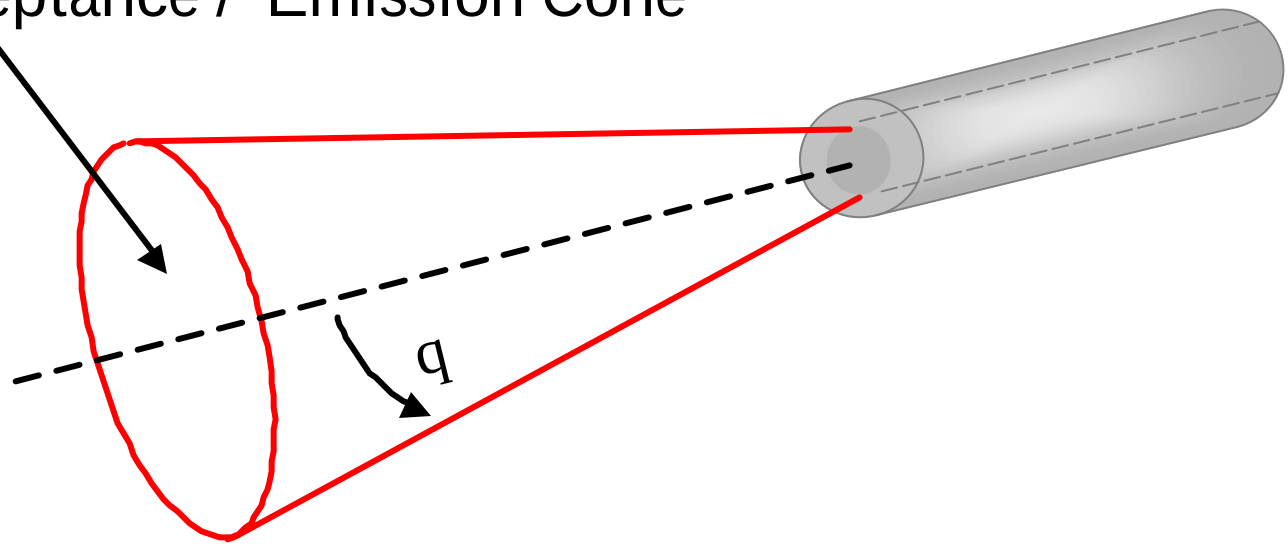
Basic Step-Index (SI) Fiber Design

- Most common designs: 100/140 or 200/280 µm
- Plastic optical fiber (POF): 0.1 - 3 mm ∅, core 80 to 99%



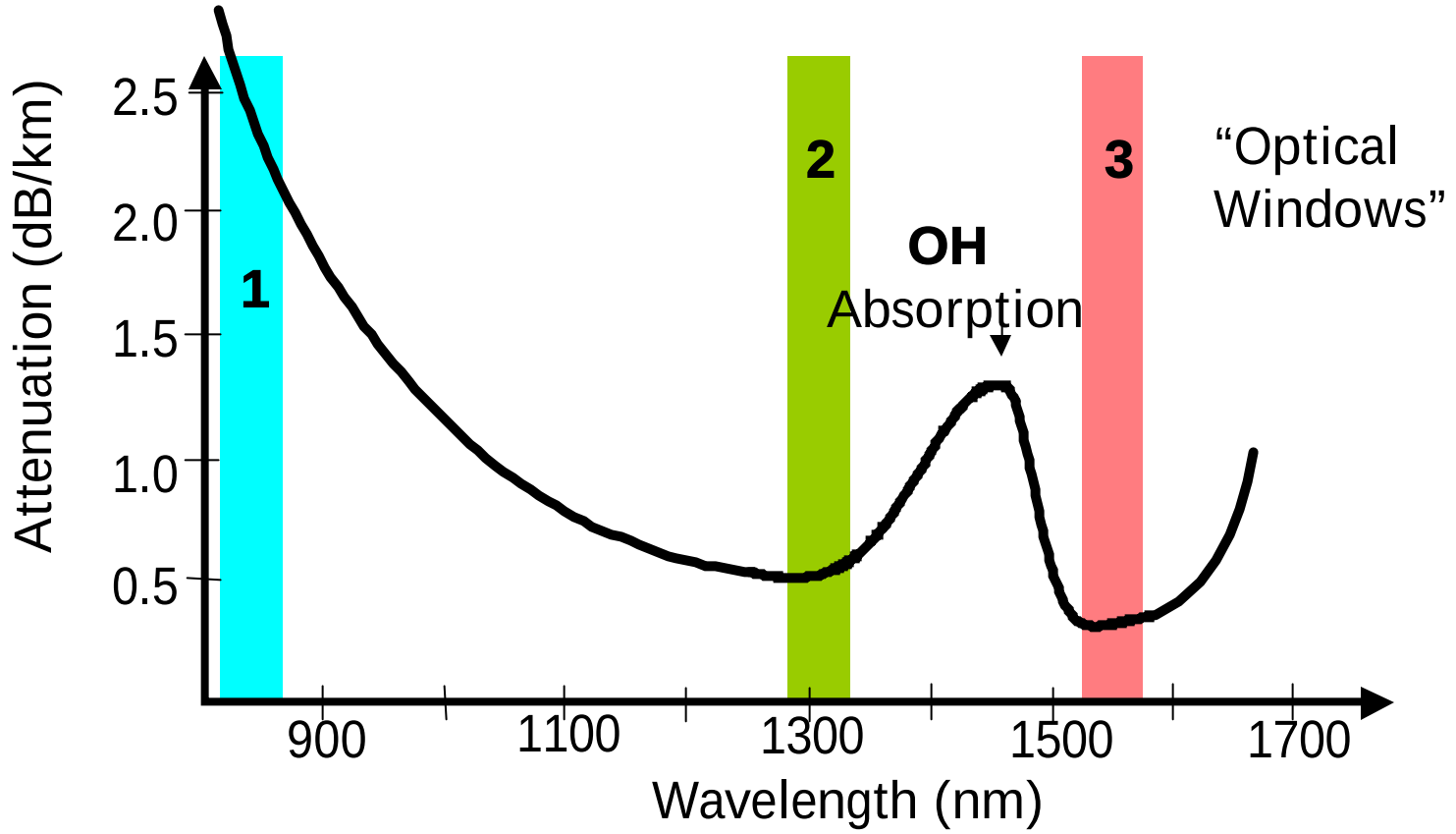
Numerical Aperture (NA)

Acceptance / Emission Cone



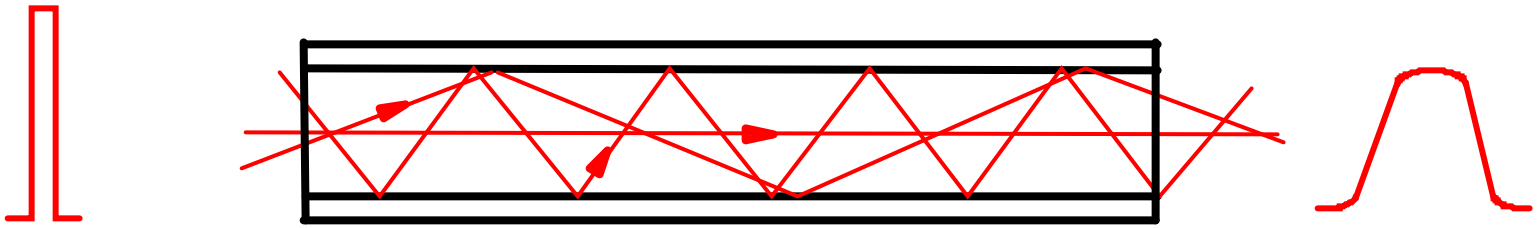
$$NA = \sin q = \sqrt{n^2_{core} - n^2_{cladding}}$$

Attenuation In Silica Fibers



Main cause of attenuation: Rayleigh scattering in the fiber core

Step-Index Multimode (MM) Dispersion



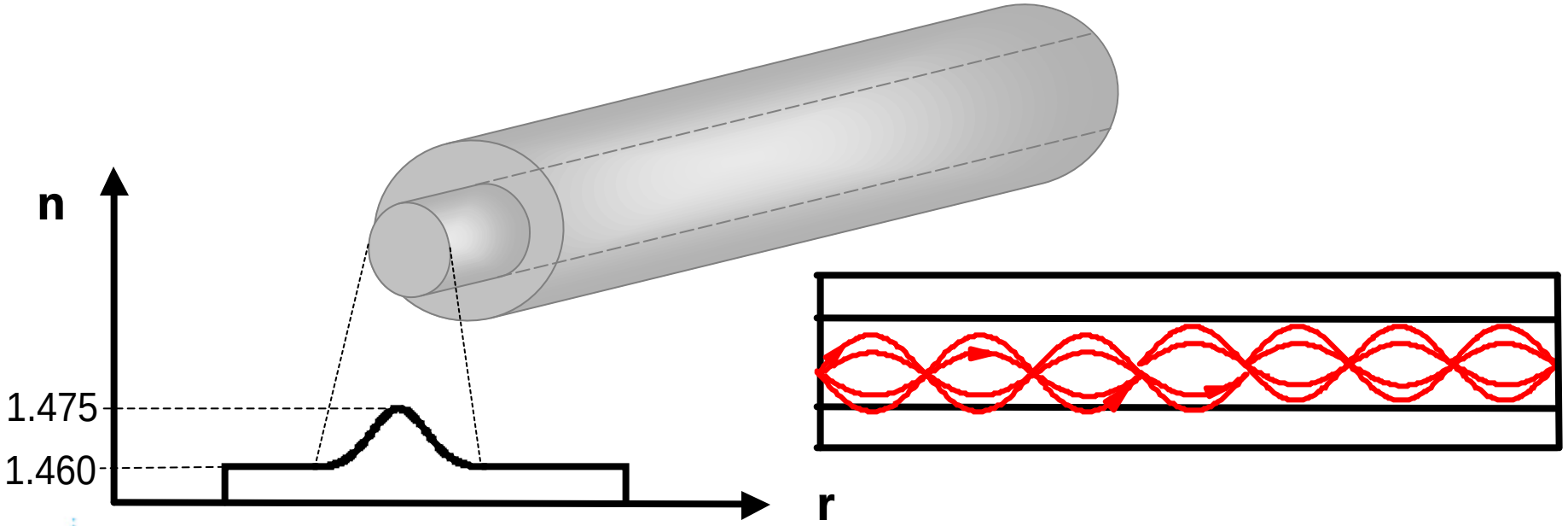
Pulse broadening due to multi-path transmission.

Bitrate x Distance product is severely limited!

100/140 µm Silica Fiber:	~ 20 Mb/s • km
0.8/1.0 mm Plastic Optical Fiber:	~ 5 Mb/s • km

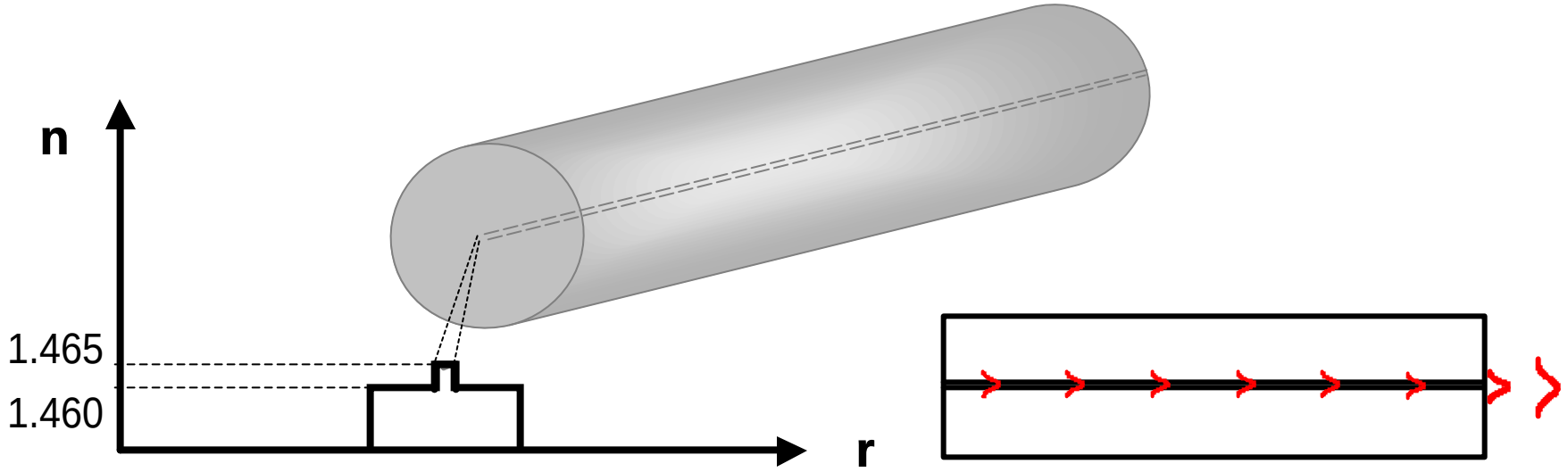
Gradient-Index (GI) Fiber

- Doping profile designed to minimize “race” conditions
  (“outer” modes travel faster due to lower refractive index!)
- Most common designs: 62.5/125 or 50/125 μm, NA ~ 0.2
- Bitrate x Distance product: ~ 1 Gb/s • km



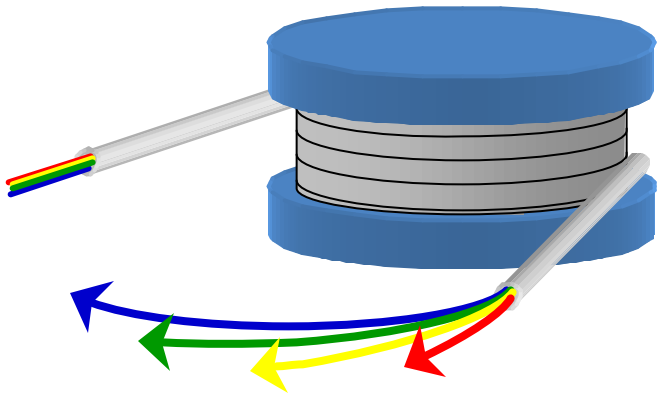
Single-Mode Fiber (SMF)

- Step-Index type with very small core
- Most common design: 9/125 µm or 10/125 µm, NA ~ 0.1
- Bitrate x Distance product: up to 1000 Gb/s • km
  (limited by CD and PMD - see next slides)



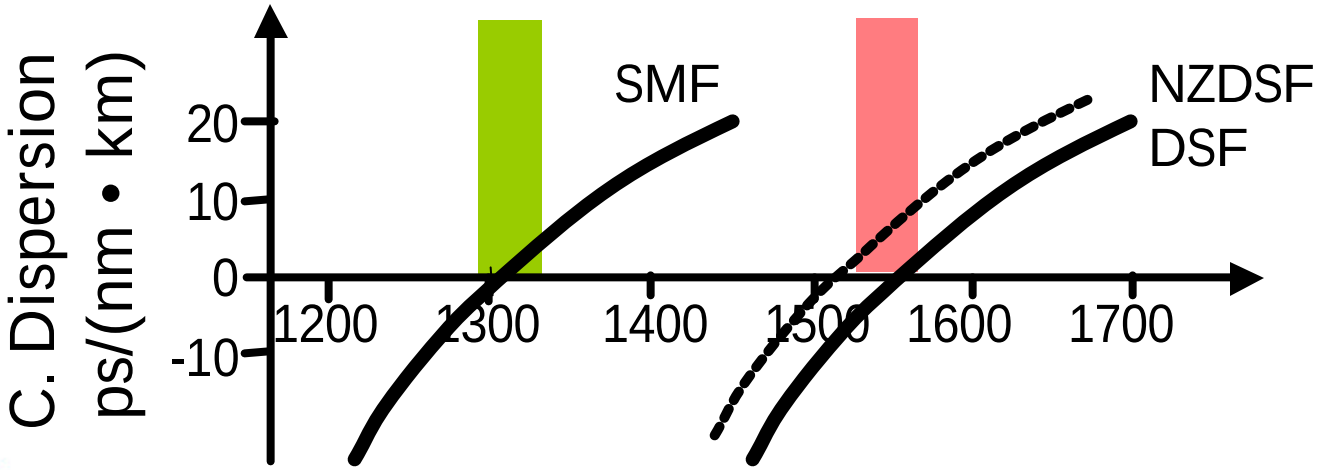
Chromatic Dispersion (CD)

- Light sources are NOT monochromatic
  (linewidth of source, chirp effects, modulation sidebands)
- Different wavelengths travel at slightly different speeds
  (this effect is called “Chromatic Dispersion”)
- Chromatic dispersion causes pulse broadening
  (problem at high bit rates over long distances)
- Standard single-mode fiber:
  - 1300 nm window has lowest CD
  - 1550 nm lowest loss



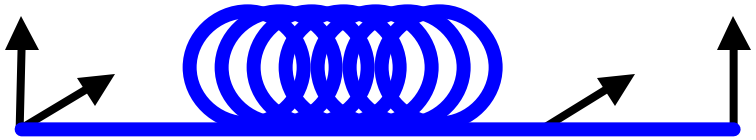
Dispersion-Shifted Fiber (DSF)

- Additional doping to shift zero dispersion to 1550 nm
  - Now 1550 nm lowest loss AND lowest dispersion
  - Can cause nonlinear effects in DWDM systems (see later)
- Non-Zero Dispersion Shifted Fiber (NZDSF)
  - Low dispersion around 1550 nm and low nonlinear effects
  - Requires chromatic dispersion compensators on long distances



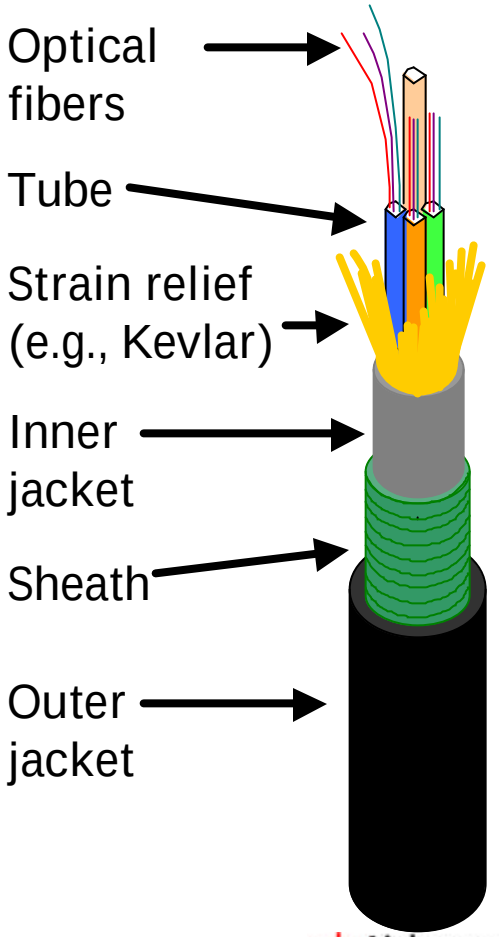
Polarization Mode Dispersion (PMD)

- Single-mode fiber actually transmits two modes
  - Modes have opposite states of polarization
  - Severe limitation at 10 Gb/s over distances > 50 km
- Power is randomly coupled between the two modes
  - PMD of a link fluctuates significantly over time
- Components can exhibit PMD as well
  - mostly constant PMD
  - manufacturers trying to minimize it by design



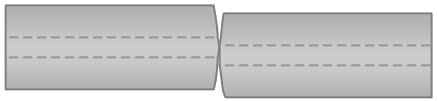
Cable Designs

- Mechanical design:
  - Indoor, outdoor, submarine
  - Local or national building and construction codes may apply
- Electrical designs:
  - No metal or electrical wires at all
  - Power wires (supply for remote amplifiers or regenerators)

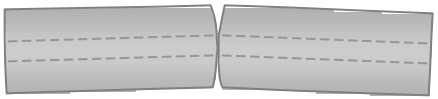


Issues Of Connecting Fibers

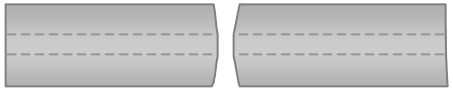
Offset



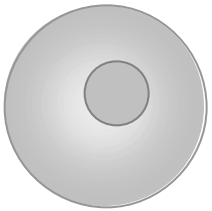
Angular Misalignment



Separation

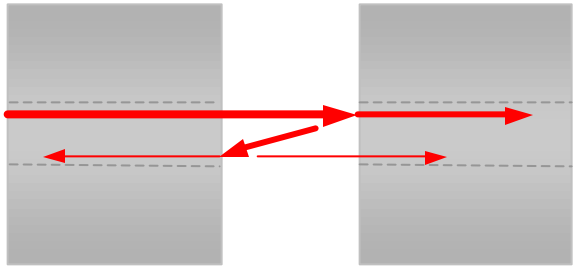


Core Eccentricity



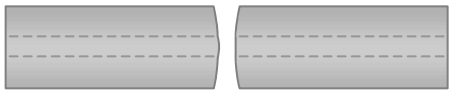
Core Ellipticity

Reflections & Interference



Connector Types

Air Gap

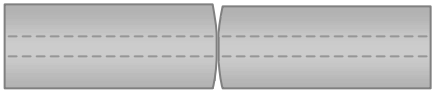


Medium insertion loss:
typ. 0.5 dB

Worst return loss:
< 14 dB (Fresnel)

Common multimode fiber connector

Physical Contact (PC)

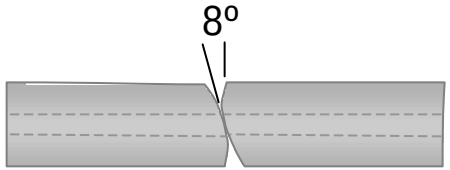


Lowest insertion loss:
< 0.25 dB

Good return loss:
> 40 dB

Common single-mode fiber connector

Angled Physical Contact (APC)



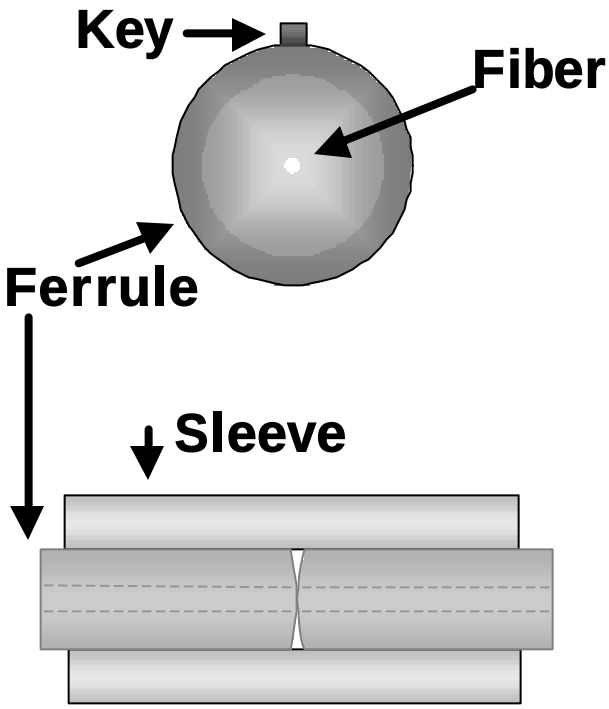
Highest insertion loss:
0.4 to 0.9 dB

Best return loss:
> 60 dB

Cable TV, high performance systems

Connector Technology

- Ultra-high precision
  - Optical axis aligned to better than ±1 µm (single-mode)
  - Physical contact of the glass end surfaces necessary
- Connector cleanliness is paramount
  - special cleaning and inspection required



Connector Brands

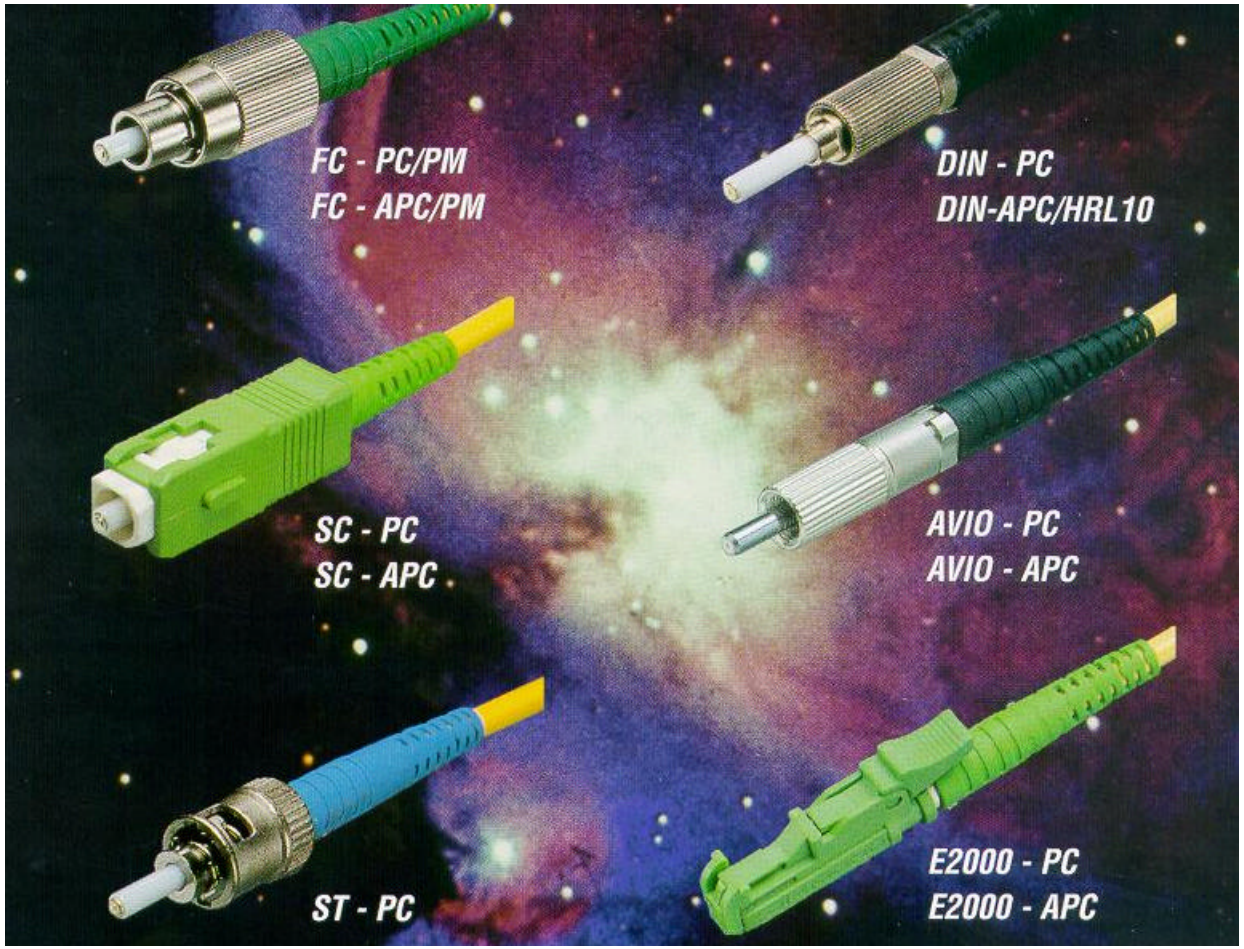
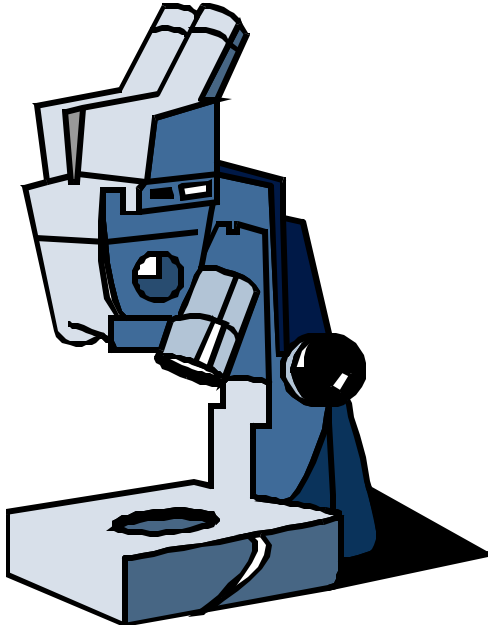
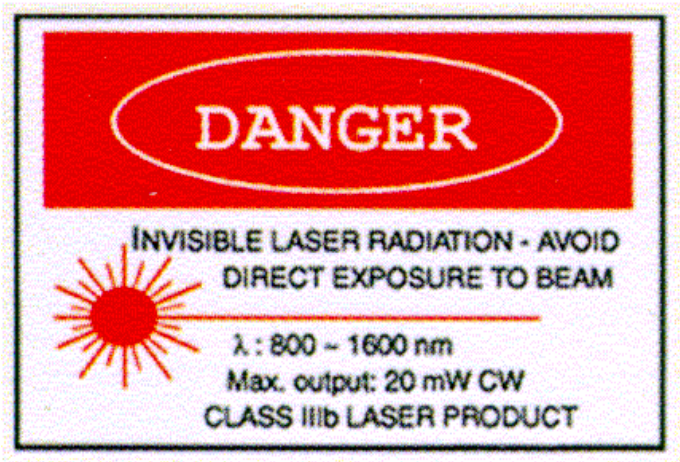


Photo courtesy of: Diamond SA

Connector Inspection

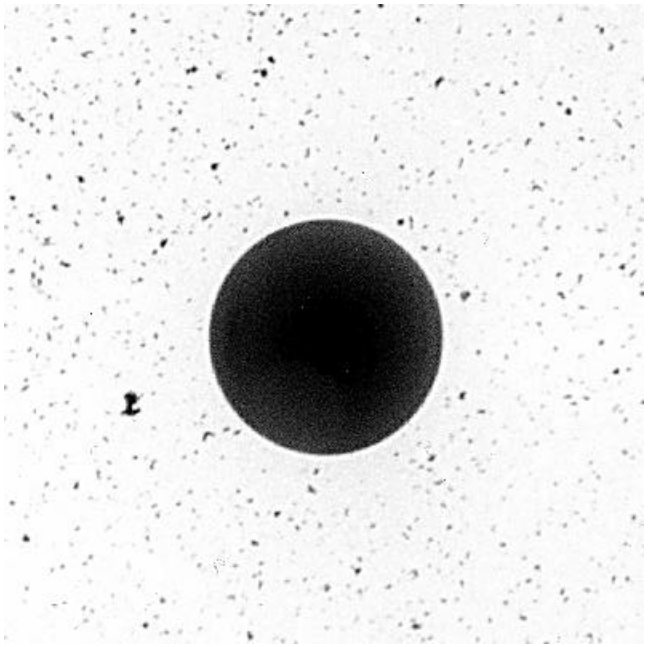


Inspection Tool

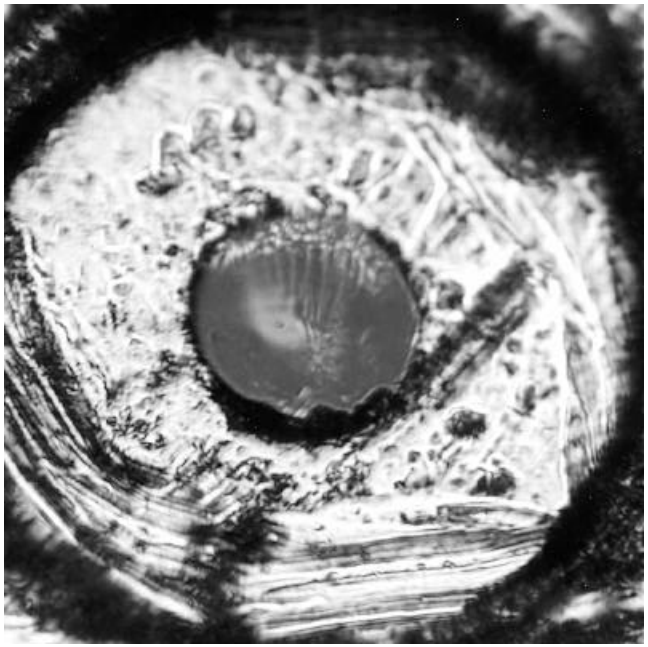


Don't stare into the laser beam
(with your remaining eye)

Connector Care



New Connector



Damaged Connector

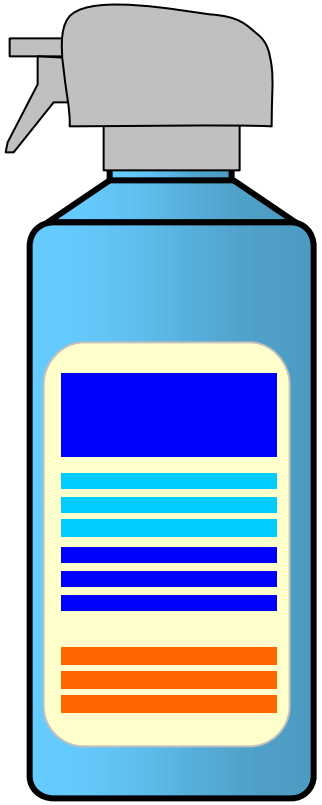
Connector Cleaning

Variety of cleaning methods in use today

Example:

Clean connector tips with Isopropyl (96% medical alcohol) using *adhesive free* cotton swabs

Immediately dry it with *dust-free, non residue* compressed air



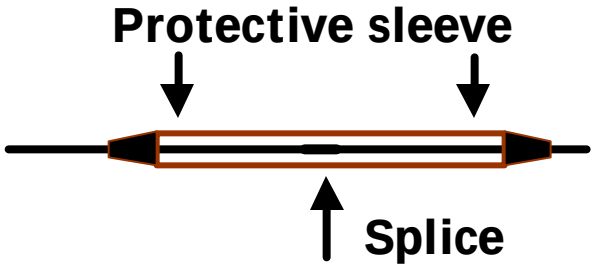
Filtered Air

Isopropyl Alcohol

Pure Cotton Swabs

Splices

- Fusion Splices
  - Most common permanent fiber connection
  - Very high performance and reliability
  - Insertion loss 0.01 to 0.1 dB, no reflection
  - Automated splicing tool costs $10k to $50k



- Mechanical Splices
  - Permanent and non-permanent types
  - Insertion loss 0.1 to 0.5 dB
  - Index-matching liquid used to minimize loss & reflections
  - Epoxy or UV hardened elastomer based
  - Less expensive tools ($100 to $1,000) required

Review Questions

1. What are commonly used fiber types?

2. What is dispersion and what can cause it?

3. What are good connector care habits?