AN OVERVIEW OF OPTICAL FIBER FUNDAMENTALS

IEEE
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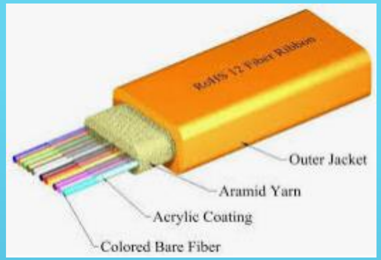
IEEE | LONG ISLAND SECTION

Long Island Consultants Network

DISCLAIMER

- Fiber optics (FO)Technology has entered into many different areas
- Today's presentation portrays FO as used in telecommunications systems
- Some other uses not presented herein include :
  - Medical & Health care
    - Endoscopes in which glass fibers arrayed in rows and columns emulate digital based screens in which each FO strand represents a pixel, Biomedical and MRI sensors, Oral cavity illumination in dentistry, and Fiber-based laser interferometers
  - Geology
    - seismic tomography, detection of sink holes, and early warning earthquake detection
  - Military & Aerospace
    - acoustic sensing, chemical sensing, and laser systems. Detecting chemical agents in the air. laser-based weapons systems for transmitting high-energy laser beams, fiber optic gyroscopes
  - Consumer Electronics & Automotive
    - Audio Interconnects (TOSLink), temperature sensors, automotive Ethernet

IDEAL CABLES



- A cable is the path (channel) between the transmitter and the receiver.
- An ideal cable should have:
  - Minimal Attenuation
  - Frequency Response
  - Minimal Dispersion
  - Minimal Latency
  - Physical Properties:
  - Predictable
  - Repeatable
  - Consistent
  - Universal
  - Reasonable Cost

	Indoor	Indoor / Outdoor	Outdoor
Standards	ICEA 596 GR-409	ICEA 696 GR-409 / GR-20	ICEA 640 ICEA 717 (Drop) GR-20
Operational Temperature Range	(-20 °C to +70 °C) Riser (0 °C to +70 °C) Plenum	(-40 °C to +70 °C)	(-40 °C to +70 °C) (-50 °C to +70 °C)
UV Resistance	No	Yes	Yes
Water Blocked	No	Yes	Yes
Tensile rating	50 to 300 lbs.	300 to 600 lbs.	300 to 600 lbs.
Crush rating	50 to 100 N/cm	110 to 220 N/cm	110 to 440 N/cm

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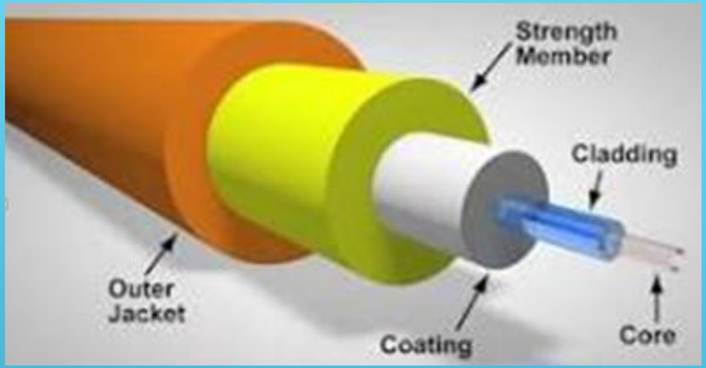
BASIC DEFINITIONS



- Optical Fiber
  - Glass filament of coaxial construction that conducts light via total internal reflection
- Core
  - The center, the axial part of an optical fiber serves as the light transmission area of the fiber. The core has an index of refraction > the surrounding cladding. (light speed is slower in the core)
- Cladding
  - Glass surrounding the core of an optical fiber that has an index of refraction < the core
- Single Mode Fiber (SMF)
  - SMF allows for only one pathway, or mode, of light to travel within the fiber. The core size is typically 8.3 µm. Usually used for long distances.
- Multimode Mode Fiber (MMF)
  - MMF allows more than one mode (path) of light. Common MM core sizes are 50 µm & 62.5 µm. Multimode fiber is better suited for shorter distances.

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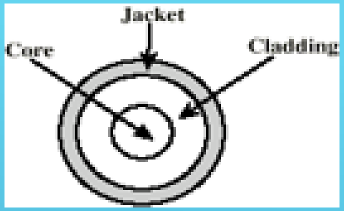
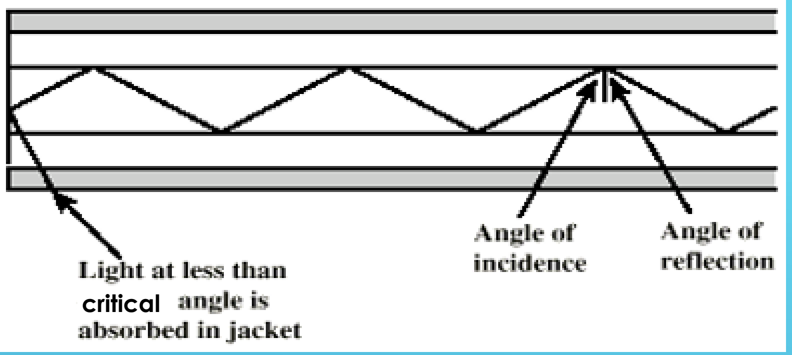
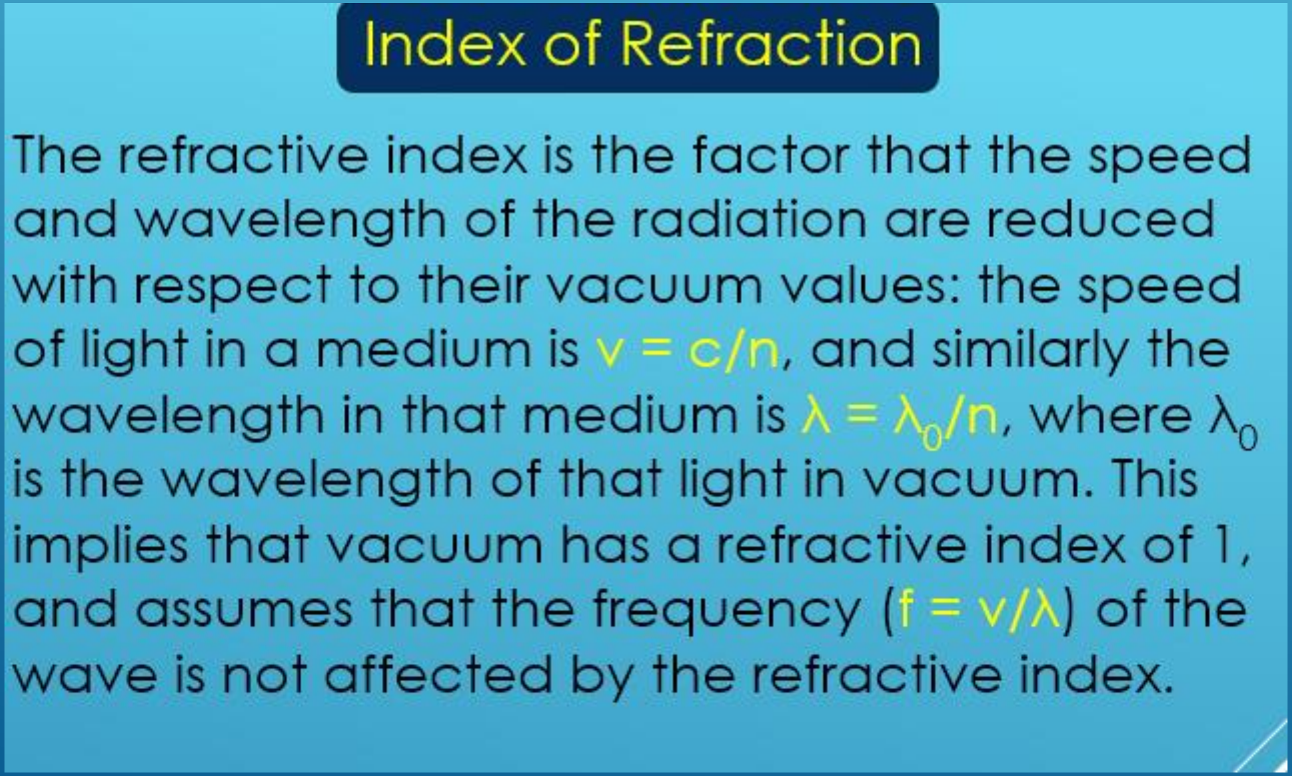
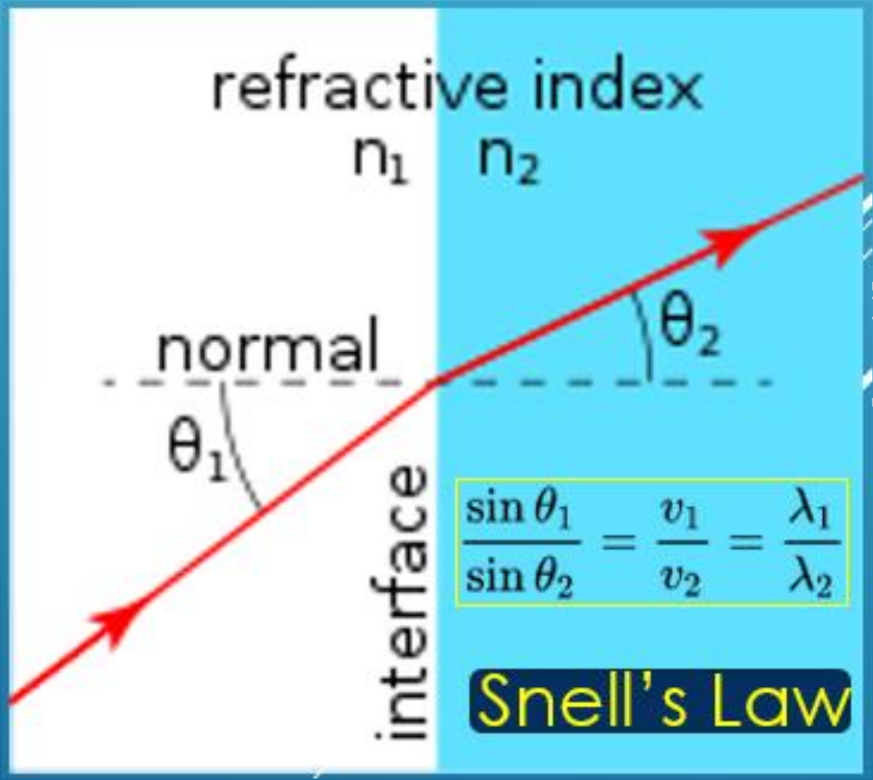
Refraction & Reflection





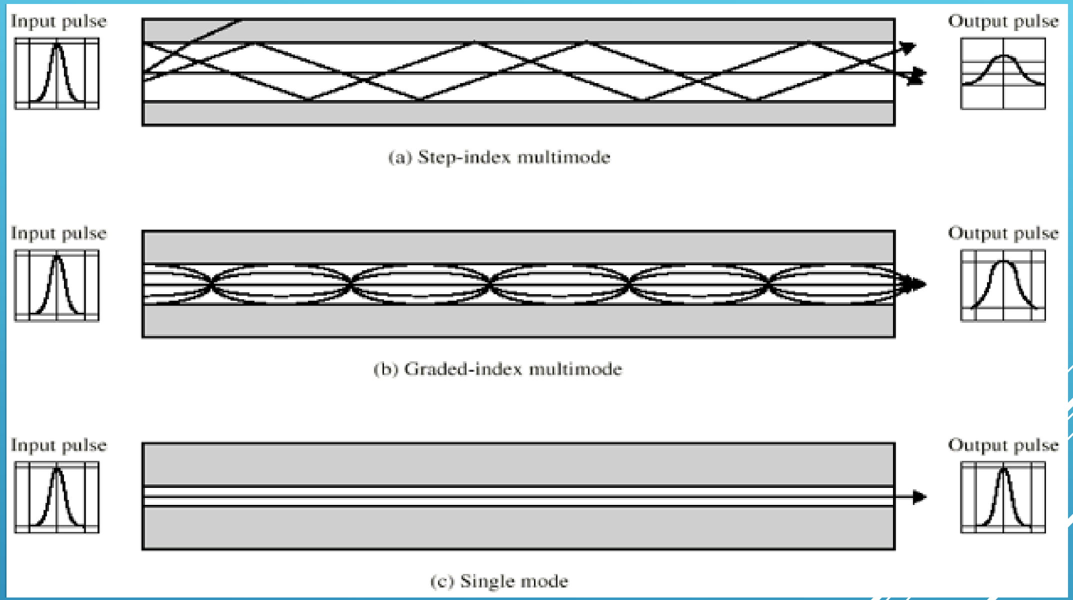
- **Total Internal Reflection**
  - If the cladding has a lower index of refraction than the core, a distinct angle exists for which no light is refracted. Light is completely reflected back into the core material. Maximum light can be transmitted through the light guide only if total internal reflection occurs at the core-cladding interface.





FIBER TYPES

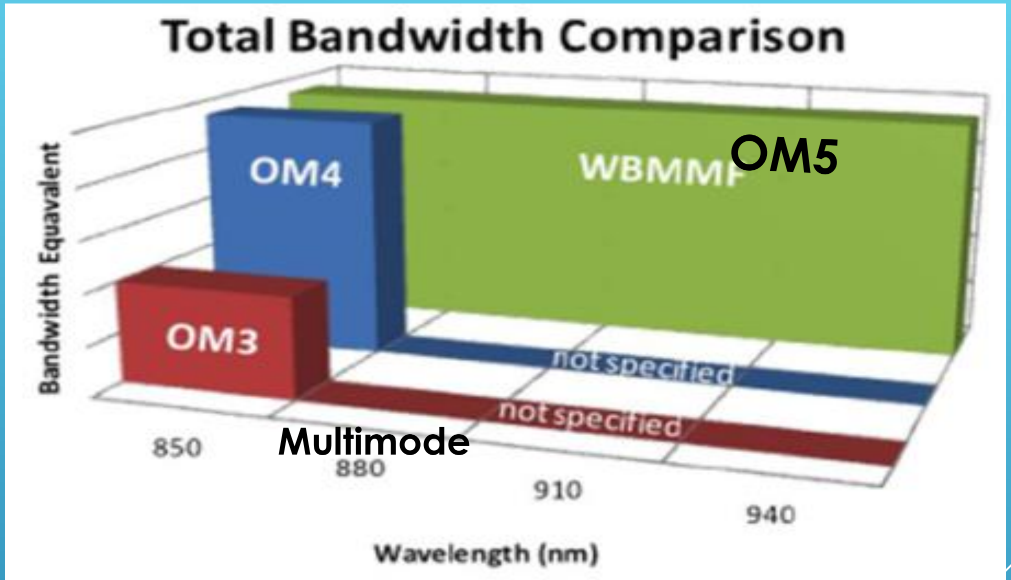
- For **step index multimode fibers**, the index of refraction is constant within the core and constant within the cladding. Step index fibers have a constant index profile over the entire cross section.
- **Graded index multimode fibers** have a non-linear, rotationally symmetric index profile, which falls off from the center of the fiber outwards. The index of refraction is reduced from the middle outwards. The rays travel in a spiral form around the optical axis. (used in LANs)
- **Single mode fibers** support one confined transverse mode in which light propagates inside the fiber. (used in WANs)



Clad fibers are necessary for transmitting light over long distance. If cladding were not used, the environment (atmosphere, gases, dirt) would be the cladding material. Absorption greatly reduces the transmitted light. For total internal reflection, some of the energy in the electric field penetrates the cladding and is known as the evanescence field. Typically the penetration depth is 5 times the respective wavelength. Cladding material requires high optical performance because a significant portion of the energy is transmitted in it.

FIBER PERFORMANCE FACTORS

- **Dispersion**
  - Modal – core radius >> λ
    - Measured in MHz – km at a specific transmission λ
    - Function of Δ between longest & shortest guided light path (typical good quality, 2000 MHz-km for MMF)
    - Note: SMF does NOT exhibit modal dispersion
  - Chromatic
    - Different spectral components of a transmitted pulse travel at different velocities (function of transmitter)
  - The fiber's temperature affects the intensity of the light's backscatter.

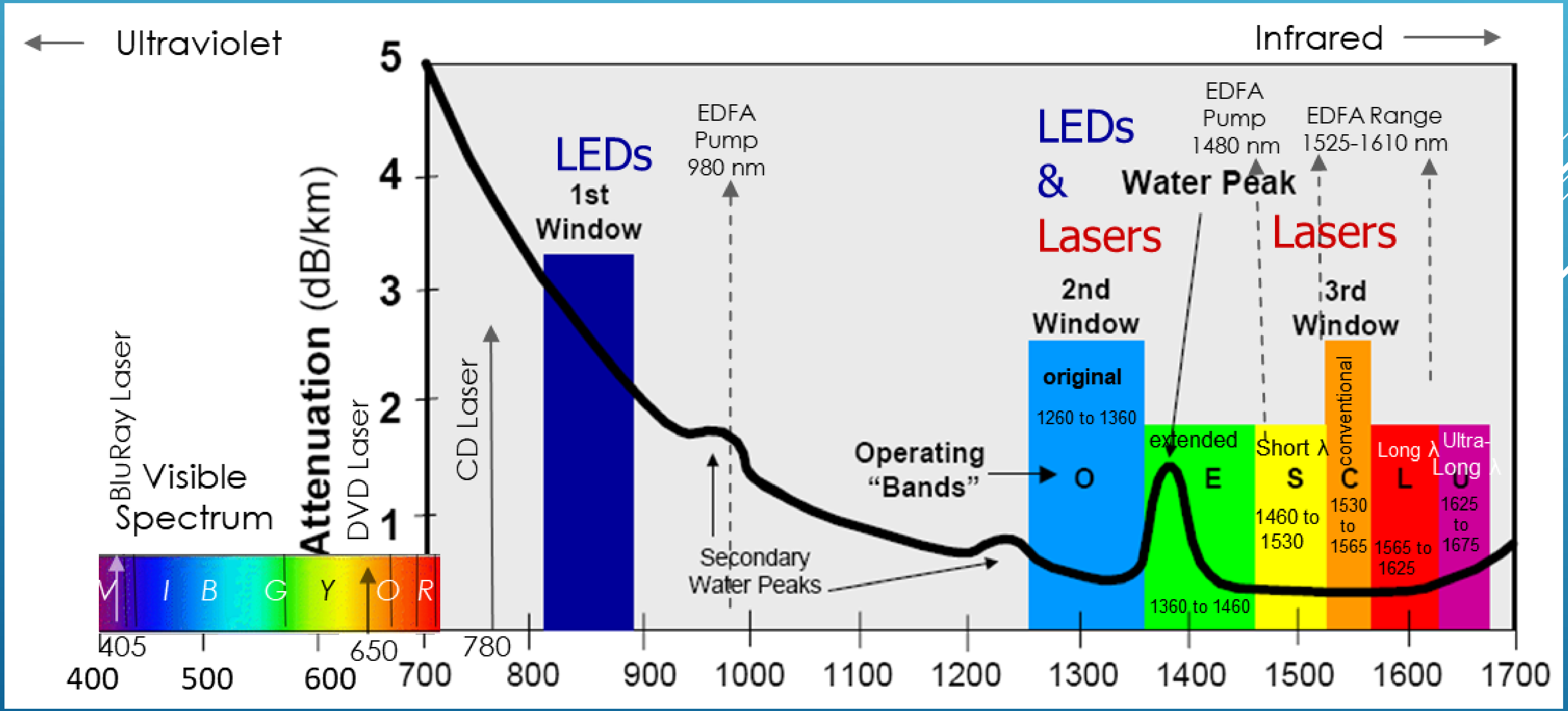


(described in the industry using primarily the **ISO/IEC 11801** designations)

Multimode Fiber Type	Industry Standards					Attenuation - Typical Cabled Max. (dB/km)		Bandwidth (MHz-km) Overfilled Launch (OMBc)		Effective Modal Bandwidth (EMB) (also known as Laser BW)	
	ISO/IEC 11801-1 Nov. 2017	IEC 60793-2-10 May 2019	TIA-568.3 2021 draft	TIA/EIA 492AAAF April 2020	ITU-T Dec. 2008	850nm	1300nm	850nm	1300nm	850nm	953nm
62.5/125	OM1	A1-OM1	~~TIA 492AAAF (A1-OM1)~~	A1-OM1	—	3.5	1.5	200	500	—	—
50/125	OM2	A1-OM2	~~TIA 492AAAF (A1-OM2)~~	A1-OM2	G.651.1	3.5	1.5	500	500	—	—
50/125	OM3	A1-OM3	TIA 492AAAF (A1-OM3)	A1-OM3	—	$3.0^{(2)}$	1.5	1500	500	2000	—
50/125	OM4	A1-OM4	TIA 492AAAF (A1-OM4)	A1-OM4	—	$3.0^{(2)}$	1.5	3500	500	4700	—
50/125	OM5	A1-OM5	TIA 492AAAF (A1-OM5)	A1-OM5	—	3.0	1.5	3500	500	4700	2470

FIBER PERFORMANCE FACTORS

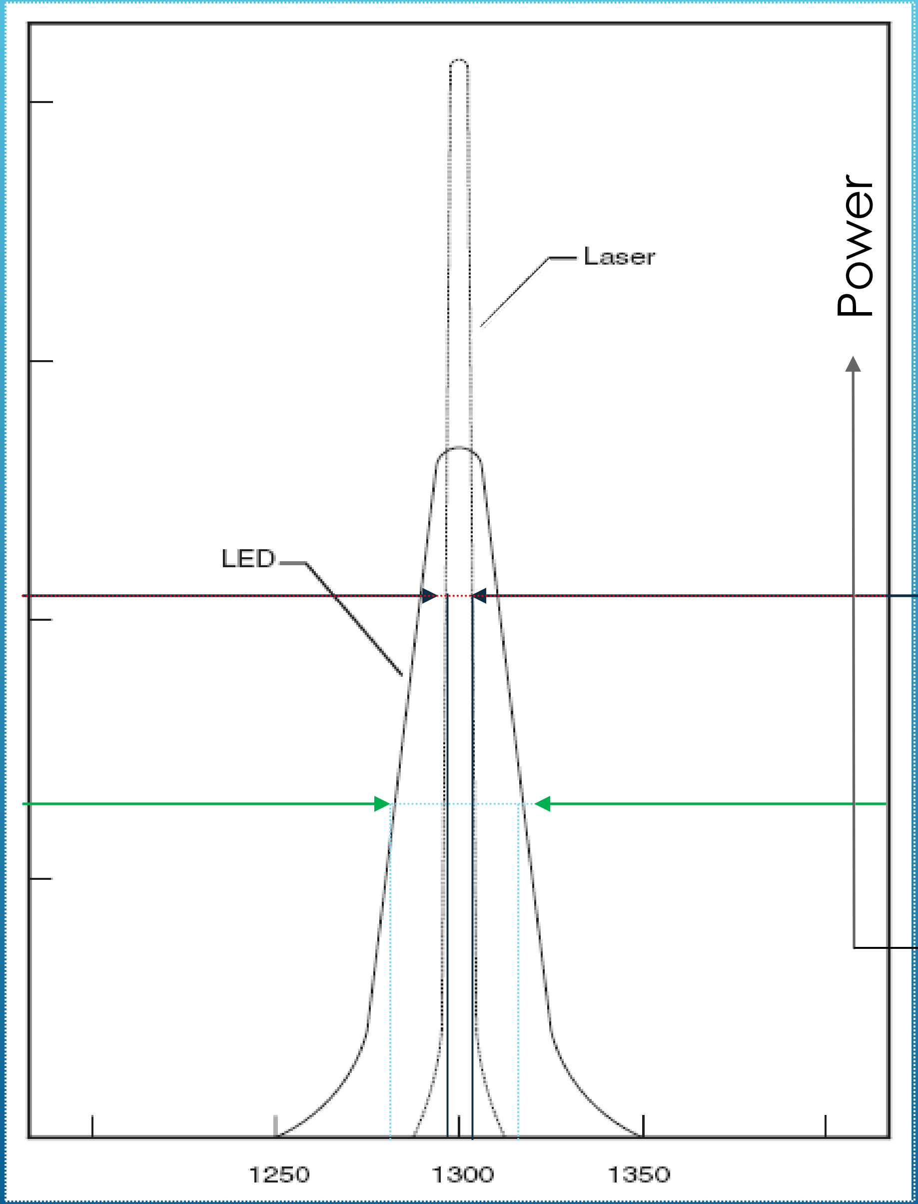
- Attenuation (dB per km)
  - Most feasible λ's are designated as "Windows"
- Propagation Velocity (function of index of refraction of fiber core)
  - If a fiber stretches, the propagation time changes indicating that the fiber is under some sort of strain
  - Time $N_{vp} \approx 5.085$ μS per Km
- Mechanical
  - Tensile Strength
  - Bend Radius
  - Temperature



Wavelength (nm)

FIBER OPTIC TRANSMITTER COMPARISON

The total power emitted by a transmitter is distributed over a range of wavelengths spread around the center wavelength. This range is the spectral width. Spectral width is measured in nanometers. Spectral widths vary from narrow for lasers (several nanometers) to wide for LEDs (from tens to hundreds of nanometers) depending on the type of source used. Wide spectral widths lead to increased dispersion of light pulses as the light pulses propagate through an optical fiber.

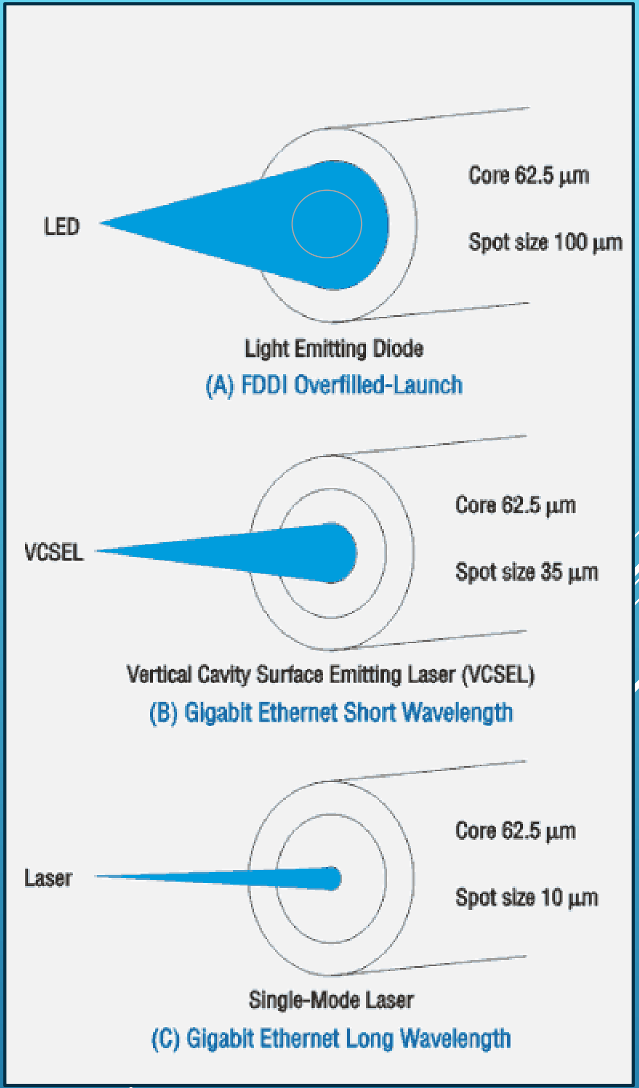


Spectral width is usually given as the range of wavelengths emitted with an intensity level greater than or equal to one half of the peak intensity level or full width half maximum (FWHM) spectral width.

Laser Spectral Width

LED Spectral Width

Measured in µW



820 nm	LED	2Km
1300 nm	Laser	10Km
1550 nm	Laser	40Km

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FIBER OPTIC RECEIVERS

Key parameters of receiver performance are Receiver Sensitivity, Bandwidth, & Dynamic Range

- Receiver Noise includes:
  - Thermal Noise (KTB) results from the random motion of electrons in a conducting medium.
  - Shot Noise is caused by current fluctuations due to the discrete nature of charge carriers.
  - Dark Current Noise is current that continues to flow in the photodiode without any incident light.
  - Quantum Noise results from the random generation of electrons by the incident optical radiation.

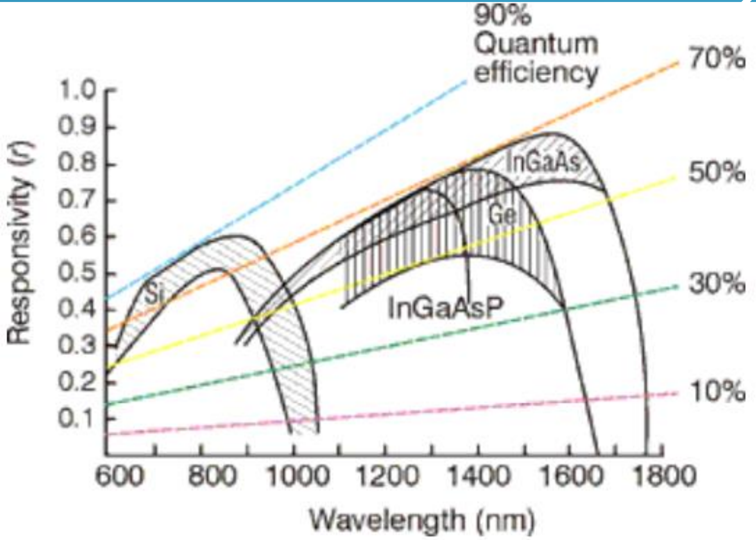
- Responsivity is the ratio of the optical detector's incident optical input power to the output power
  - Detector linearity means that the electrical output power is linearly proportional over a wide range to the optical input power.

- Response Time (bandwidth) of a photodiode depends on the thickness of the detector active area and the detector RC time constant. A high speed response requires short transit times and low capacitance. Changes to photodiode parameters optimizing transit time & capacitance affect quantum efficiency, dark current, and coupling efficiency.
  - Transit Time is the time it takes electrons to travel out of the detector active area.

- Semiconductor material choices greatly affect receiver performance

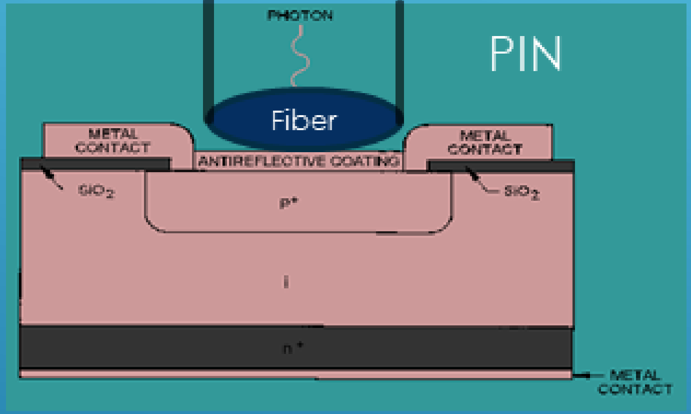
WAVELENGTH RANGES FOR COMMONLY USED PHOTODIODE MATERIALS

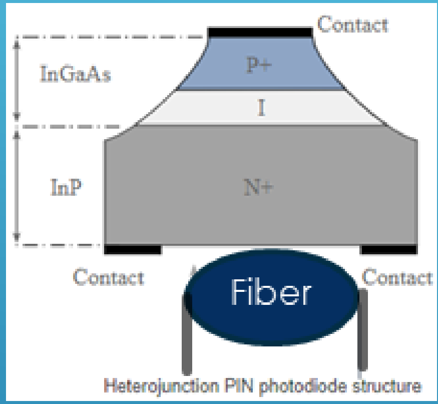
MATERIAL	WAVELENGTH SENSITIVITY (NM)
Germanium	800 - 1700
Indium gallium arsenide	800 - 2600
Lead sulphide	~1000 - 3500
Silicon	190 - 1100

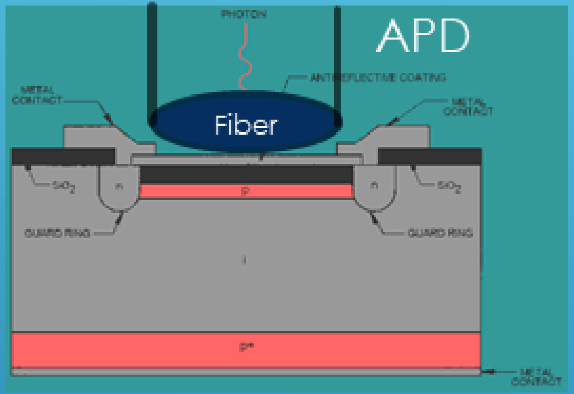


PIN & APD PHOTO DETECTOR RECEIVERS

- **Positive-Intrinsic-Negative (PIN) Photodiode** and **Avalanche Photodiode (APD)** are the principal optical detectors used in fiber optic telecommunications systems.
- **PIN Photodiodes** are used as the detector in most applications. (less expensive)



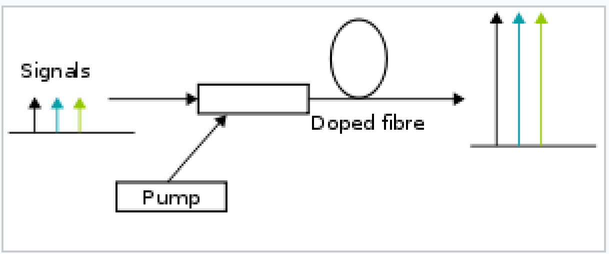




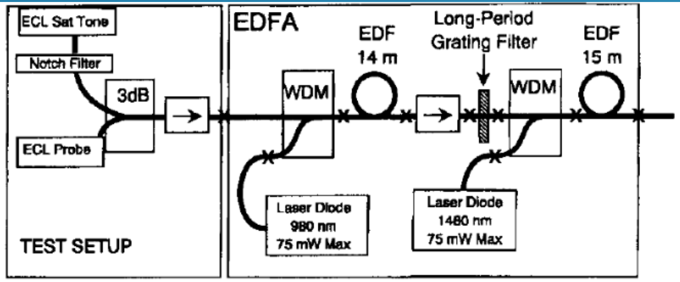
- In **Avalanche Photodiodes** (APD), a high Reverse-Bias voltage (≥ 100 volts) is applied across the active region where Avalanche Multiplication occurs when accelerated electrons collide with other electrons in the semiconductor material, causing some of them to become part of the photocurrent.
  - The **Response Time** of APDs accounts for the avalanche build-up time in addition to transit time and RC time constant.
  - **Avalanche Photodiodes** are mostly used for high-speed applications and applications where extreme sensitivities are required. (Expensive, require HV support circuits)

FIBER OPTIC LIGHT AMPLIFIERS

- **An Erbium-Doped Fiber Amplifier (EDFA) amplifies light traversing a fiber to overcome attenuation**
- Amplification occurs in the third transmission window (C band) of silica-based optical fiber. In an EDFA, the core of a silica fiber is doped with trivalent erbium ions (Er3+) and is pumped with a laser. Gain occurs in the 1550 nm region. The EDFA bandwidth varies from a few nm up to ~80 nm.
  - Typical EDFA calls for Conventional, or C-band amplifiers (from ~1520 nm to ~1565 nm), Long, or L-band amplifiers (from ~1565 nm to ~1610 nm). Both bands normally use two different amplifiers, each optimized for one of the bands.
  - A longer length of doped fiber is used in L-band amplifiers that allows a lower inversion level, thus emitting at longer wavelengths (due to the band-structure of Erbium in silica) while still providing gain.
  - EDFAs have 2 pumping bands – 980 nm and 1480 nm.
  - The 980 nm band has a higher absorption cross-section and used where low-noise performance is required. The 1480 nm band has a lower, but broader, absorption cross-section and used for higher power amplifiers.
  - Both C and L bands are used in typical optical amplifiers.
- Noise figure in an ideal EDFA is 3 dB, while practical amplifiers have noise figures of 6 – 8 dB
- EDFAs and co-doped erbium-ytterbium doped fiber amplifiers have gains of 30–40 dB and 25 dBm of output saturation power.



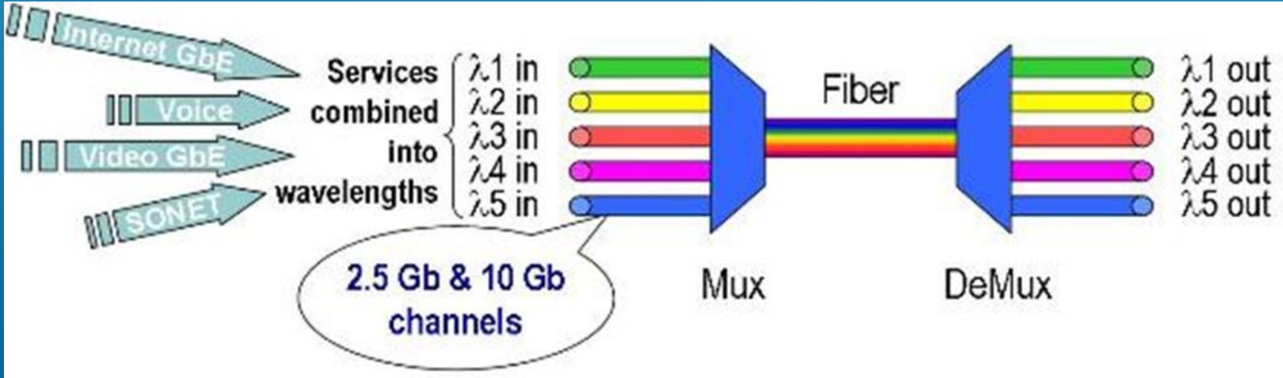
Schematic diagram of a simple Doped Fiber Amplifier



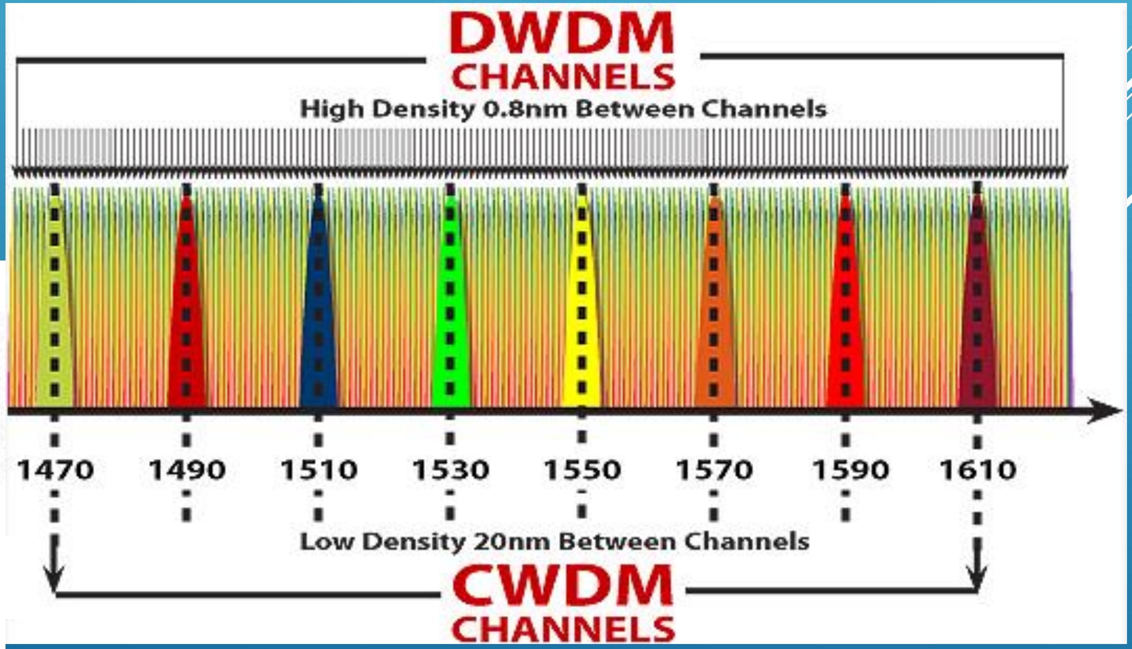
Schematic of an EDFA designed to provide uniform gain over the 1530–1570-nm bandwidth using an optical filter containing several long-period fiber gratings. The two-stage design helps to reduce the noise level.

WAVELENGTH DIVISION MULTIPLEXING

- Wavelength division multiplexing (WDM) combines different wavelengths (colors or λ) in a single fiber and at the opposite end separates them out again
  - WDM multiplies capacity of a single fiber by the number of λ's used
- The input end of a WDM system is a coupler combining all inputs into one output fiber.
- A demultiplexer collimates the light from the input fiber into a narrow, parallel beam of light shining on a grating (a mirror like device that works as a prism) that separates the light into different λs by launching them at different angles. Optics capture each λ and focus it into a fiber, creating a separate output for each λ of light.
- WDM commonly uses two types of systems:
  - Coarse Wavelength Division Multiplexing (CWDM)
  - Dense Wavelength Division Multiplexing (DWDM)

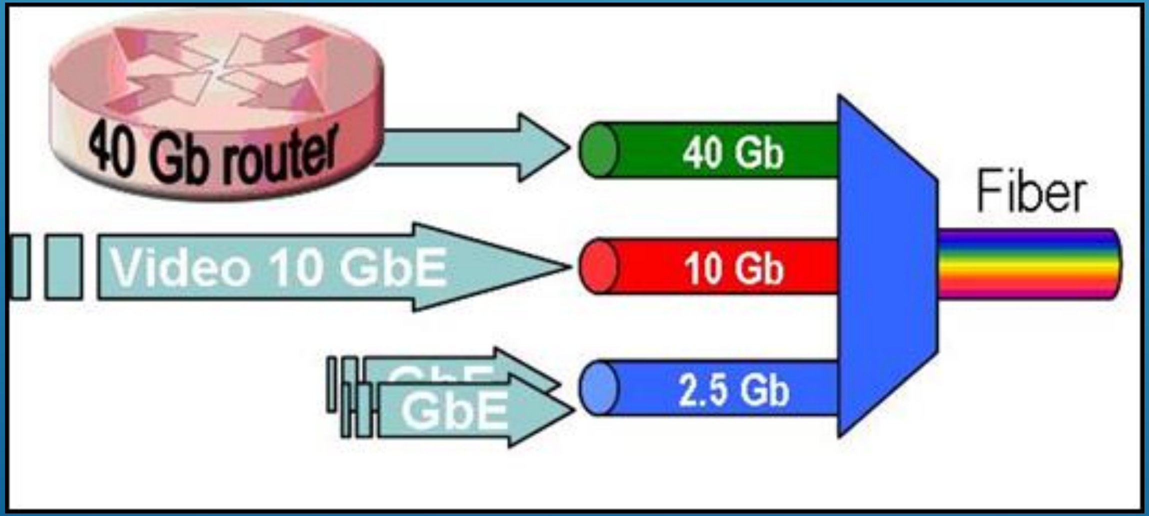


Wavelength Division Multiplexing



CWDM

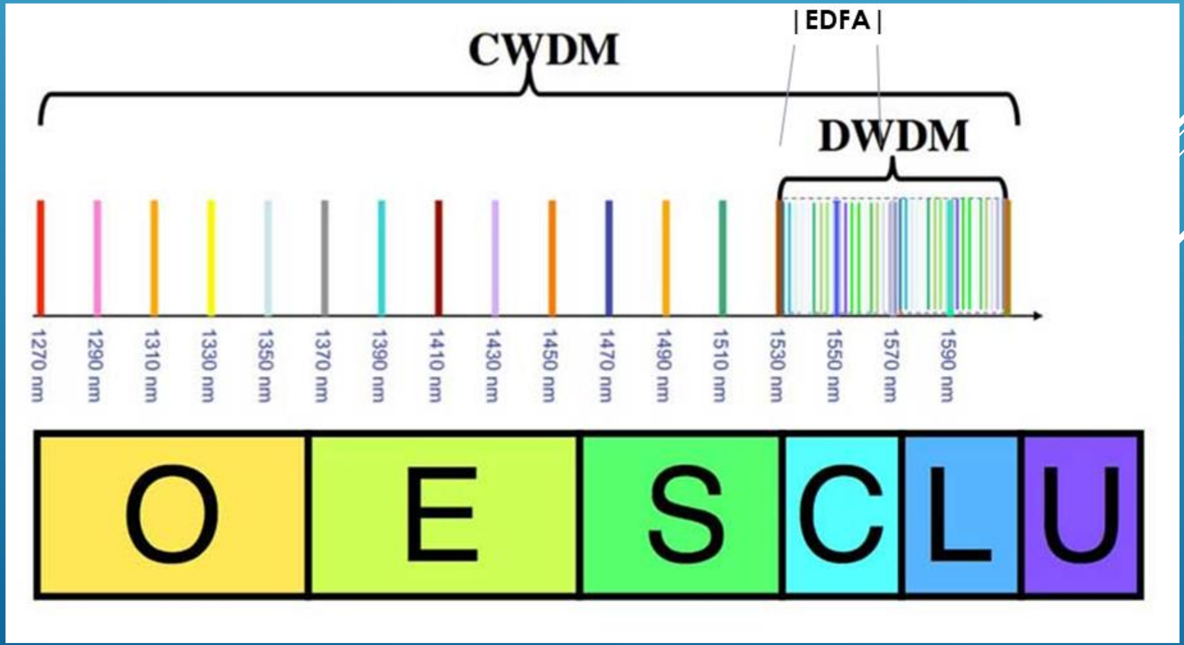
- CWDM is coarse WDM operating between 1270 to 1590 nm.
- CWDM equipment typically uses wavelengths about 20 nm apart.
- CWDM transmits up to 16 channels & uses wider spacing between channels.
- CWDM's wider spacing of 20 nm, (compared to DWDM) tolerates much higher temperature fluctuations and device variations.
  - Less expensive terminal equipment
- The IEEE 10GBASE-LX4 10 Gbps standard is a CWDM system in which four wavelengths near 1310 nm are used to carry 10 Gbps of aggregate data
- Passive Optical Networks (PON) such as FIOS service from Verizon uses CWDM



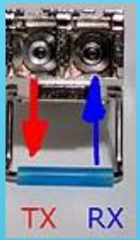
DWDN

- Standard dense C-band DWDM ITU channels consist of 0.8 nm (100GHz) wavelength spacing for 40 channels or 0.4 nm (50GHz) spacing for 80 channels.
- ITU G694.1 defines the DWDM wavelength range as 1528.77nm (196.1 THz) to 1563.86nm (191.7 THz).
  - DWDM is typically used within the wavelength limits of optical amplifiers
- DWDM systems must maintain more stable wavelength than those needed for CWDM due to the closer λ spacing of the wavelengths. Precision temperature control of the laser transmitters in DWDM systems prevents drift away from a very narrow frequency window of a few GHz.
- DWDM operates at a higher level in the communications hierarchy, such as the Internet backbone and is used with higher modulation rates. The market is smaller for DWDM devices with very high performance. The factors of smaller market volume and higher performance result in DWDM systems typically being more expensive than CWDM.

  Innovations in DWDM transport systems include pluggable and software-tunable transceiver modules operating across 40 or 80 channels.



FIBER OPTIC TRANSCEIVER MODULES



- Small Form Factor Pluggables
- An SFP interface is a modular slot for a media-specific transceiver. With SFPs *(compared to fixed interfaces)* individual ports can be equipped with different types of transceivers as required.
- A QSFP interface is similar to SFP, but slightly larger and capable of much higher data rates
- Pluggable modules allow fiber equipment manufacturers to customize their products according to customer requirements, ultimately realizing lower cost solutions

Name	Standard	Introduced	Status	Backward compatible	MAC block to a PHY chip	Media	Connector	Lanes
100 Mbit/s SFP	SFF INF-8074i	2001-05-01	current	none	MII	Fiber, Twisted Pair	LC, RJ45	1
1 Gbit/s SFP	SFF INF-8074i	2001-05-01	current	100 Mbit/s SFP*	SGMII	Fiber, Twisted Pair	LC, RJ45	1
1 Gbit/s cSFP			current			Fiber	LC	2
10 Gbit/s SFP+	SFF SFF-8431 4.1	2009-07-06	current	SFP	XGMII	Fiber, Twisted Pair, DAC	LC, RJ45	1
25 Gbit/s SFP28	SFF SFF-8402	2014-09-13	current	SFP, SFP+		Fiber, DAC	LC	1
50 Gbit/s SFP56			current	SFP, SFP+, SFP28		Fiber, DAC	LC	1

Name	Standard	Introduced	Status	Backward compatible	MAC block to a PHY chip	Media	Connector	Lanes	Notes
QSFP types									
4 Gbit/s QSFP	SFF INF-8438	2006-11-01	current	none	GMII			4	
40 Gbit/s QSFP+	SFF SFF-8436	2012-04-01	current	none	XGMII	Fiber, DAC	LC, MTP/MPO	4	CWDM
50 Gbit/s QSFP28	SFF SFF-8665	2014-09-13	current	QSFP+		Fiber, DAC	LC	2	
100 Gbit/s QSFP28	SFF SFF-8665	2014-09-13	current	QSFP+		Fiber, DAC	LC, MTP/MPO-12	4	CWDM
200 Gbit/s QSFP56	SFF SFF-8665	2015-06-29	current	QSFP+, QSFP28		Fiber, DAC	LC, MTP/MPO-12	4	
400 Gbit/s QSFP112	SFF SFF-8665	2015-06-29	current	QSFP+, QSFP28, QSFP56		Fiber, DAC	LC, MTP/MPO-12	4	
400 Gbit/s QSFP-DD	SFF INF-8628	2016-06-27	current	QSFP+, QSFP28,[18] QSFP56		Fiber, DAC	LC, MTP/MPO-16	8	CWDM

COMBINATION OF TECHNIQUES

Transmission	40GbE Tx Rx	100GbE Tx Rx	400GbE Tx Rx
10G parallel lanes			Would require 40 fibers in each direction. Connector issues
25G parallel lanes	N/A		
10G or 25G with WDM and/or parallel lanes			

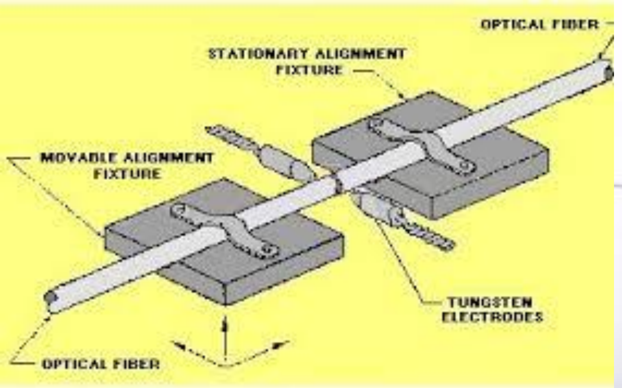
Note: Multiple lines represent parallel lanes and line with multiple colors represents WDM (multiple wavelengths within same lane).

Practical Concerns

- The primary cost of most optical networks is the optical interfaces; NOT the cables.
- A MMF network can be used with inexpensive connectors and transmitters lowering the total system cost.
- MMF fiber is a better choice for shorter distance applications such as within a data center.
- A SMF network requires more expensive transmitters and receivers to couple enough light given the small core area.
- SMF is typically used in carrier networks and supports distances of ≈40 km.

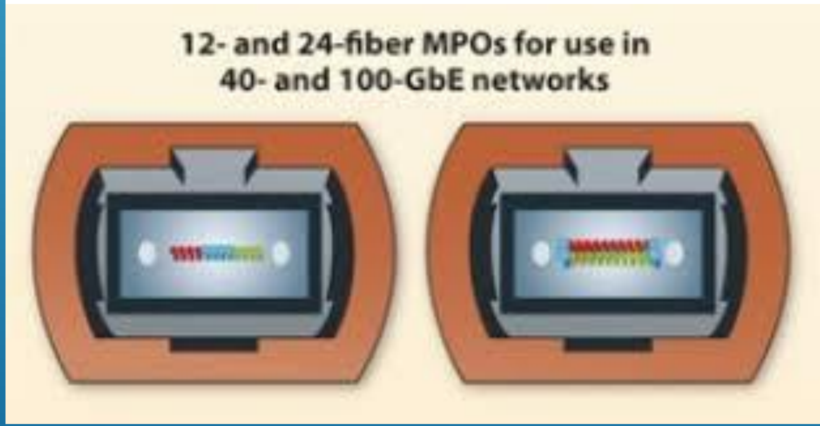
FIBER OPTIC CABLE SPLICING

- Fusion splicing melts the fiber ends together using an electric arc.
  - First the fiber ends are stripped of their protective polymer coating and outer jacket. The ends are cleaved (cut) with a precision cleaver to make them perpendicular, and then placed into holders in the fusion splicer. The splice is inspected via a viewing screen to check the cleaves before and after the splice.
  - Splicers use small motors to align the end faces together, and emit a small spark between electrodes at the gap to burn off dust and moisture.
  - Then a splicer generates a larger spark that raises the temperature above the melting point of the glass, fusing the ends permanently. The splicer controls the location and energy of the spark so that the molten core and cladding do not mix to minimize optical loss.
  - The splicer measures the optical loss by directing light through the cladding on one side and measuring the light leaking from the cladding on the other side.
  - A splice loss under 0.1 dB is typical.



FIBER CABLE SPLICING

- Mechanical splices (mated pair of connectors)
  - A fiber-optic connector is a rigid cylindrical barrel surrounded by a sleeve that holds the barrel in its mating socket. The mating mechanism can be push and click, turn and latch (bayonet mount), or screw-in (threaded). The barrel is typically free to move within the sleeve and may have a key that prevents the barrel and fiber from rotating as the connectors are mated.
  - A typical connector is installed by preparing the fiber end and inserting it into the rear of the connector body. The loss for a connector pair typically runs from 0.3 to 1.0 dB, depending on manufacturer. Use the maximum attenuation specified; for example, EIA/TIA-568A specifies a maximum optical attenuation of 0.75 dB for SC- or ST-compatible connectors.
  - Quick-set adhesive is usually used to hold the fiber securely, and a strain relief is secured to the rear.
  - After the adhesive sets, the fiber's end is polished to a mirror finish. For single-mode fiber, fiber ends are typically polished with a slight curvature that makes the mated connectors touch only at their cores. This is called a physical contact (PC) polish.
  - The curved surface may be polished at an angle, to make an angled physical contact (APC) connection. Such connections have higher loss than PC connections but greatly reduces back reflection, because light that reflects from the angled surface leaks out of the fiber core. The resulting signal strength loss is called gap loss. APC fiber ends have low back reflection even when disconnected.



FIBER OPTIC TROUBLESHOOTING

- **Problem Causes**
  - Connector is not fully engaged.
  - Quality of the connector itself,
    - Fails IEC PAS 61755-3 standards, including polish angle, fiber height, radius of curvature or apex offset.
  - Poor field termination
    - Air gaps & high insertion loss or scratches, defects and contamination on the end face of the connector.
  - Contamination is the leading cause of fiber failures — dust, fingerprints & oily substances cause excessive loss and sometimes damage connector end faces.
  - Faulty fusion splice, misalignment or incorrect polarity.
  - Poor cable management puts strain on a connector that causes misalignment
  - A connector may not be properly seated and connected with its mate often caused by worn or damaged latching mechanisms on connectors or adapters
  - Within the link itself, the fiber may have experienced microbends, macrobends, or it may be broken somewhere along the length of the fiber.
  - Even if all the connectors are high quality, free of contamination and properly terminated, if there are too many connections in a channel, the loss may exceed specifications for a given application. The same may occur from violation of distance limitations on multimode fiber, resulting in high modal dispersion.

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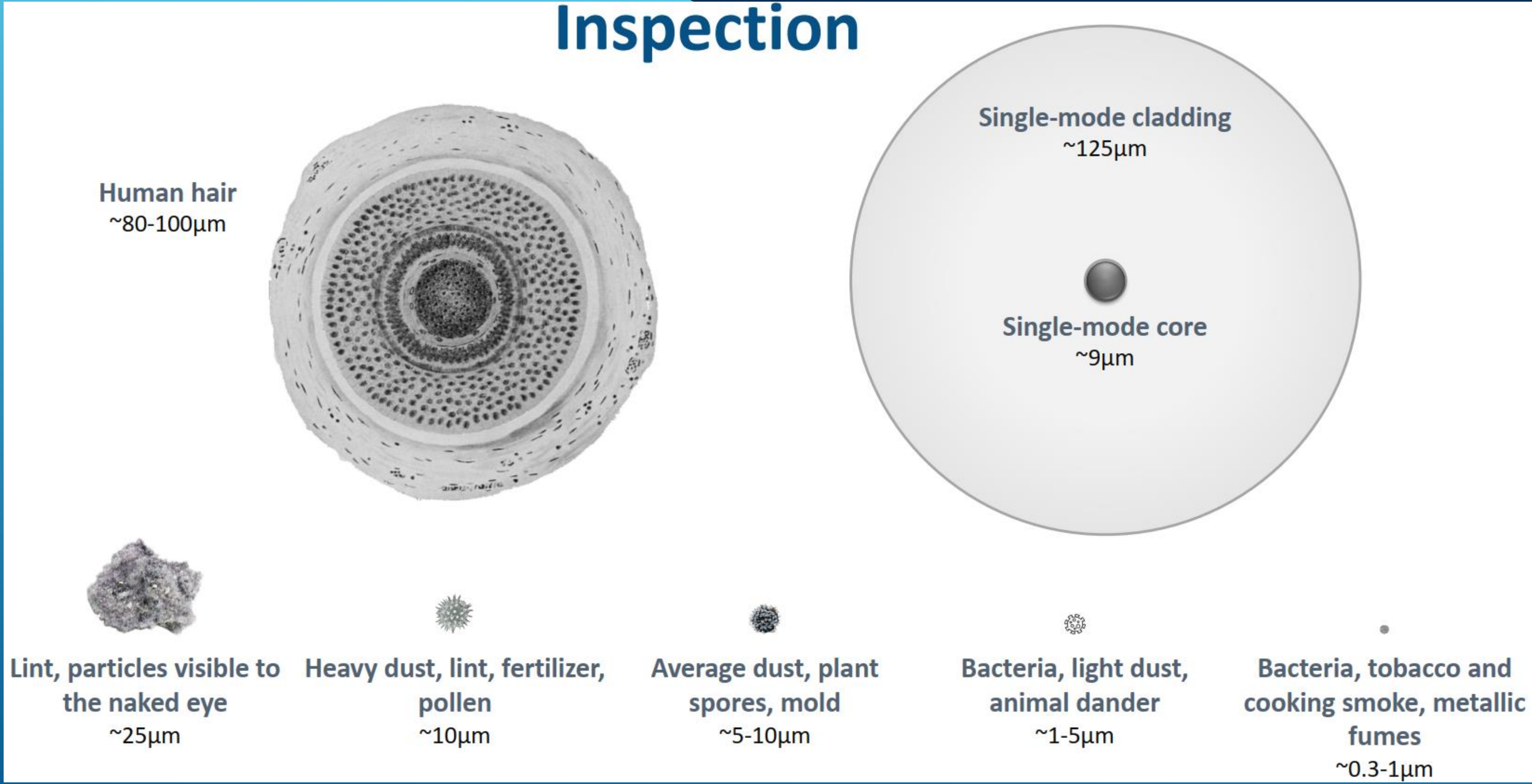
FIBER TROUBLESHOOTING TOOLS

- **Instruments & Tools**
  - Visual Fault Locators - laser light beam or flashlight that can be easily seen by eye
  - Optical Loss Test Set (OLTS) – calibrated reference light source (tx) and optical power meter (rx)that verifies output power from a device, as well as continuity and polarity.
  - Optical Time Domain Reflectometers (OTDR) provide graphical data and analysis along the entire length of a cable. It calculates signal loss based on the amount of reflected light, or backscatter, that it detects.
- The "Wiggle Test" – when loose connections, or damaged connectors are suspected use a real time trace while wiggling the connector, or pushing in on the connector to see if the connection recovers, or is permanently broken.

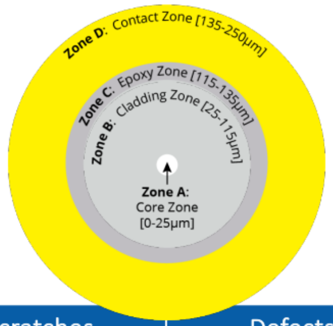
KEEP 'EM CLEAN

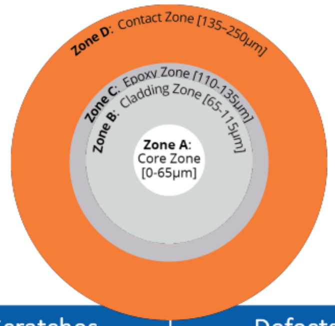
Caution: Do not stare into an optical fiber with your remaining eye!



FIBER OPTIC CLEANLINESS STANDARD

Inspection IEC 61300-3-35 Edition 3





Scratches	Defects	ZONE	Scratches	Defects
NONE	NONE	A	No Limit ≤3µm None >3µm	Four ≤5µm None >5µm
No Limit ≤3µm None >3µm	No Limit <2µm Five >2um - <5µm None >5µm	B	No Limit ≤5µm None >5µm	No Limit <5µm Five >5µm - <10µm None >10µm
No Limit	No Limit	C	No Limit	No Limit
No Limit	None ≥10µm	D	No Limit	No Limit <20µm Five >20µm - <30µm None >30µm

Edition 3 adds a requirement to check the full contact surface (250um)

Edition 3 (2022)

Zones: ~~4~~ 2

- *Epoxy Zone* (C) and *Contact Zone* (D) – Eliminated
- *Cladding Zone* – Reduced to 110µm
- Core – Some defects and scratches allowed
- Cladding – Defects <25µm allowed
- Not all inspection equipment setup

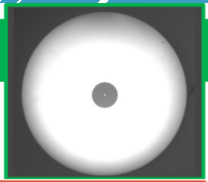
Dirt may cause a fire at exposed interfaces !

Power density is the product of the maximum power output of the light and the area of the light beam. For example, a 15-W laser beam focused onto a 150-µm diameter spot produces a power density of:

$$\frac{P}{A} = \frac{15\ \mathrm{W}}{\pi\,(0.0075\ \mathrm{cm})^2} = 85\ \mathrm{kW/cm^2}$$

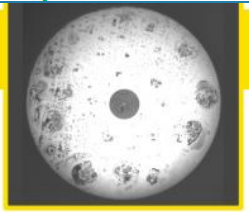
Pristine is the Ideal

The objective of inspection is to verify the endface is free of permanent defects and contamination within the contact region.

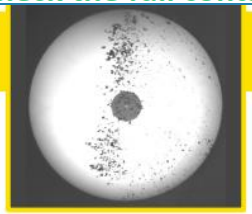


Need to Clean

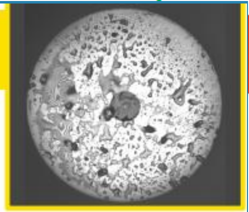
Contamination is removable.



Humidity



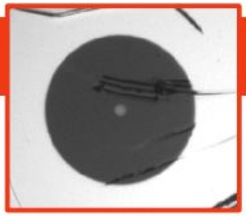
Fine Dust



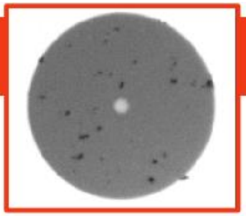
Skin Oil

Need to Replace

Scratches, embedded dust, pitting, and poorly polished surface defects are **permanent defects.**



Scratches

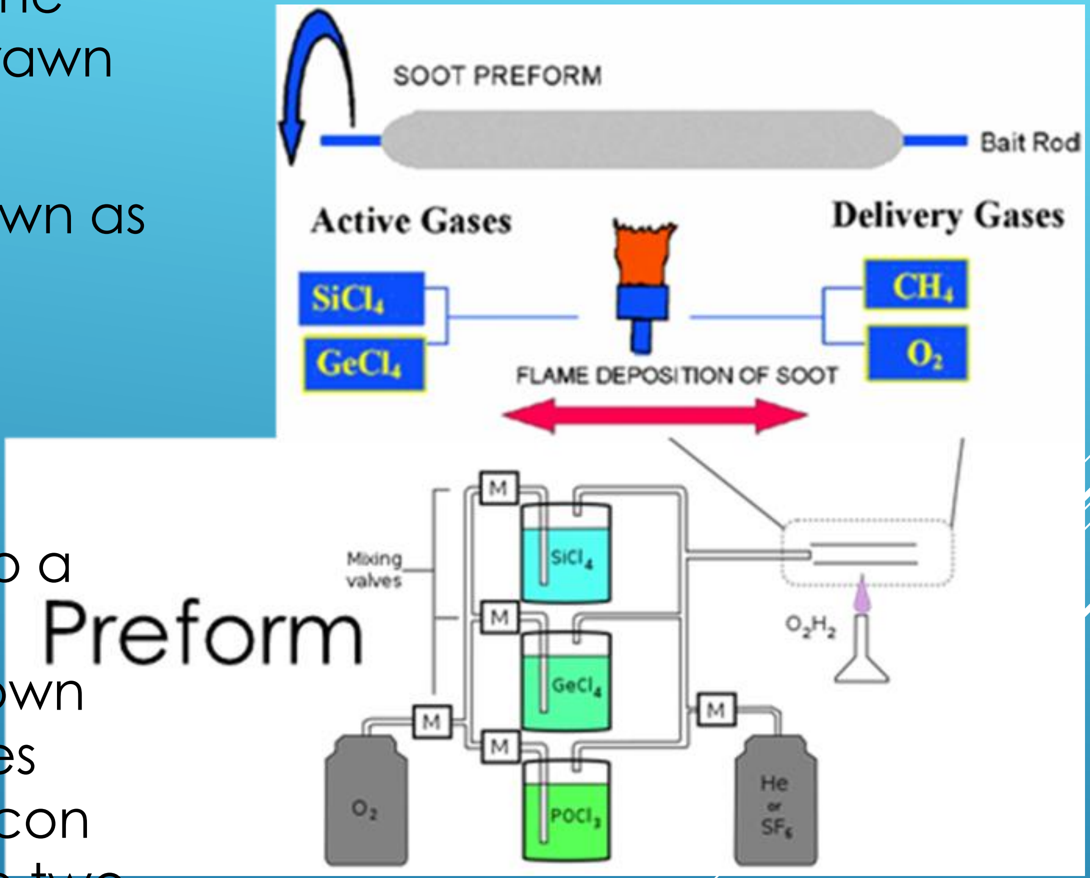


Embedded Dust

Over-polished

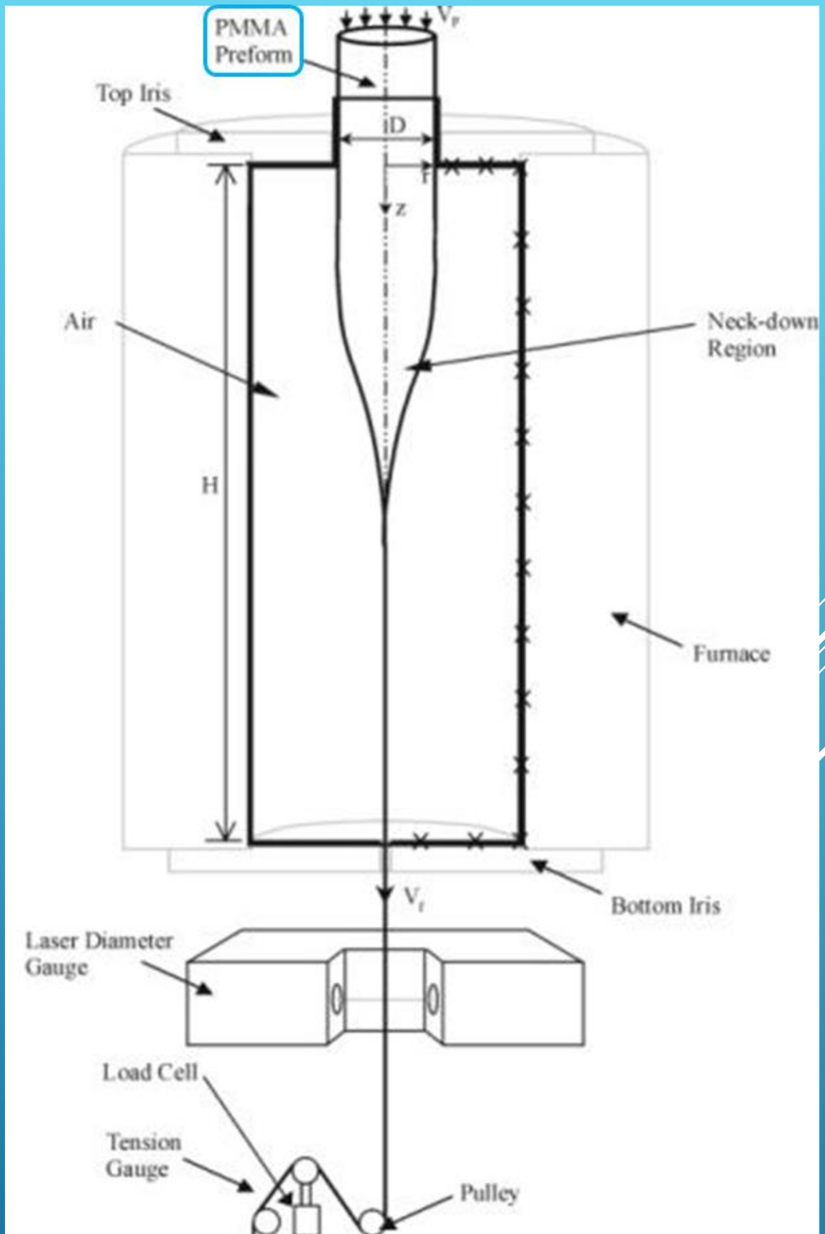
FIBER MANUFACTURING

- A Preform is a cylindrical glass blank that provides the source material from which the glass fiber will be drawn in a single, continuous strand.
- Making a preform involves a chemical process known as Modified Chemical Vapor Deposition (MCVD). This process involves bubbling oxygen through various chemical solutions including germanium chloride (GeC_{14}) and silicon chloride (SiC_{14}).
- The bubbling chemicals produce gas that goes into a hollow, rotating tube made of synthetic silica or quartz. A torch (*bunsen burner*) is moved up and down the rotating tube, resulting in very high temperatures that cause the gas to react with oxygen to form silicon dioxide ($Si0_2$) and germanium dioxide ($Ge0_2$). These two chemicals adhere to the inside of the rotating tube where they fuse together to form extremely pure glass.



FIBER MANUFACTURING

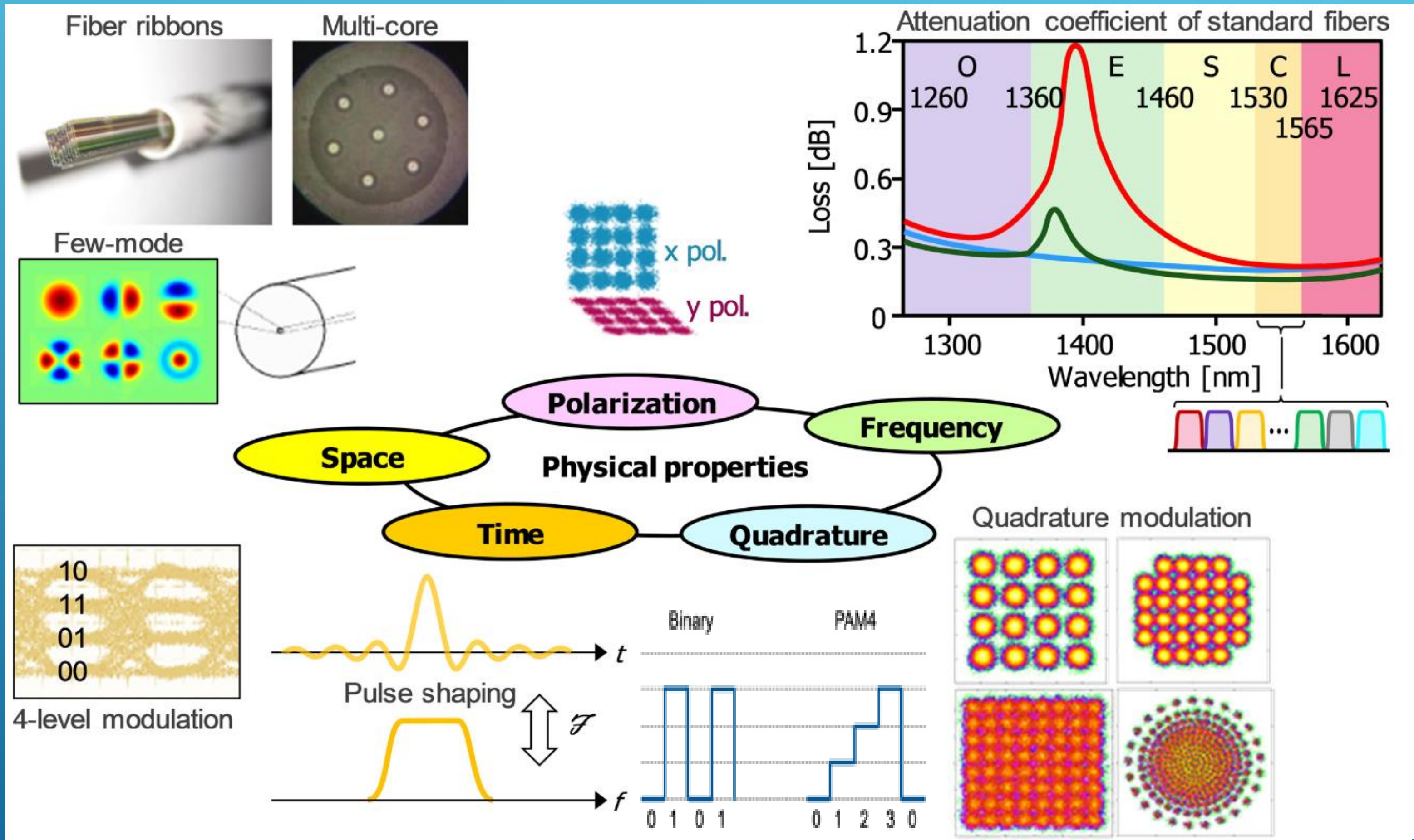
- The drawing process begins by lowering one end of the preform into an in-line furnace that produces heat in a range of 3,400 to 4,000 degrees Fahrenheit. As the lower end of the preform begins to melt, it forms a molten glob that is pulled downward by gravity. Trailing behind the glob is a thin strand of glass that cools and solidifies quickly.
- The equipment operator threads this glass strand through the remainder of the devices on the tower, which include a number of buffer coating applicators and ultraviolet curing ovens. Finally, the operator connects the fiber to a tractor mechanism that pulls the glass strand from the preform at a rate of 33 to 66 feet per second. The actual speed at which the tractor pulls the strand depends upon the feedback information the device receives from a laser micrometer that continually measures the fiber's diameter.
- At the end of the run, the completed fiber is wound onto a spool.
- Acceptance Testing post Drawing
  - Refractive index profile
  - Fiber geometry inspection, including core, cladding and coating
  - Tensile strength
  - Bandwidth capacity
  - Attenuation at different wavelengths
  - Chromatic dispersion
  - Operating temperature and humidity range



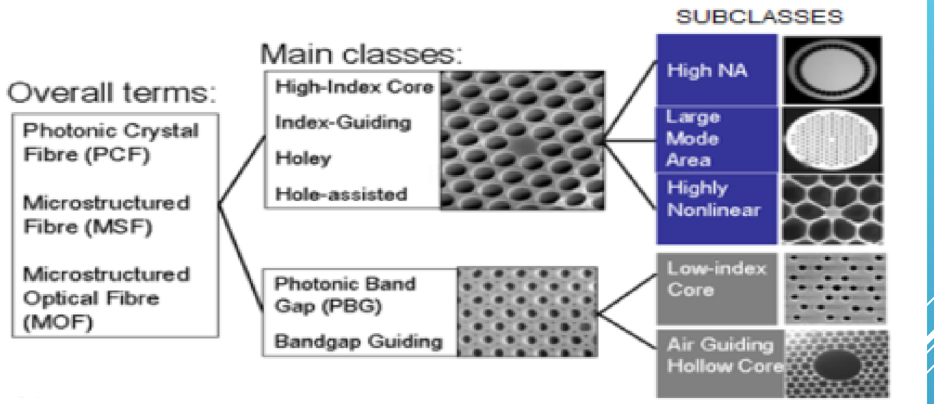
Drawing Tower

FIBER OPTIC FUTURE DIRECTIONS

Attenuation Decrease (dB/km)



ADVANCE FIBERS:



VARIOUS TYPES OF HOLEY FIBERS AND THEIR SUB CATEGORIES.

Figure 17.7

Holey fibers or Photonic crystal fibers (PCFs) can have very low effective refractive index, and can propagate light much faster than in SMFs. For example, hollow core fiber (HCF) may provide up to 31% reduced latency relative to traditional fiber optics. But there is a problem that attenuation in HCF fibers is much higher compared to already implemented standard single mode fibers (for SMF attenuation = 0.2 dB/km but for HCF attenuation = 3.3 dB/km at 1550 nm). However, it is reported even 1.2 dB/km attenuation obtained in hollow-core photonic crystal fiber. The theoretical predicted loss is only 0.001 dB/km

Capacity Increase: > 100 GHz/Lane

dense WDM spaced 0.8nm apart

Latency Decrease: < 5µS/Km

3µS/Km is free space speed of light

SERDES SERIAL SPEED DRIVES OPTICAL LANE PERFORMANCE REQUIREMENTS

- Serdes is Serializer / Deserializer *(Similar to µArt but much faster)*
  - Parallel to Series / Series to Parallel Converter Chip
- Higher data rates use pulse-amplitude modulation with 2 bits per unit interval (UI) – i.e., PAM4 – using 4 signal levels replacing the 1 bit per UI NRZ signaling used previously. The PAM definition for 224G is still being assessed, with difficult tradeoffs between:
  - More bits per UI and more signal levels
    - PAM-6, PAM-8, or use quadrature phase and amplitude modulation
  - Signal-to-noise ratios
  - Channel bandwidth required
  - Power dissipation per bit
  - Target BER (pre-forward error correction)
  - Link latency

OIF CEI projects	CEI-25G-LR	CEI-56G-LR	CEI-112G-LR	CEI-224G-LR
Timeline	2011-2014	2014-2018	2018-2022	2022-2024
Ethernet rate	100G	50/100/200G	100/200/400G	200/400/800/1600G
Switch capacity	3.2T	12.5T	25T/50T	50T/100T
Per-lane data rate	25Gbps	56Gbps	112Gbps	224Gbps
Modulation	NRZ	PAM4	PAM4	TBD
Insertion loss	25dB at 12.5GHz	30dB at 14GHz	28dB at 28GHz	TBD
Reach objectives	5m copper cable	3m copper cable	2m copper cable	1m copper cable
Pre-FEC BER target	1e-15	1e-4	1e-4	TBD
SerDes architecture	Analog	Analog/DSP	Analog/DSP	TBD

- More bits per UI reduces the channel bandwidth requirements, but increases the SNR sensitivity. Continuing with PAM-4 leverages compatibility with the 112G interface, but would then require 2X the channel bandwidth (as the UI duration will be halved).
- The IEEE 802.3df working group and the Optical Internetworking Forum (OIF) consortium are focused on the definition of the 224G interface.