Optical Fiber Cables

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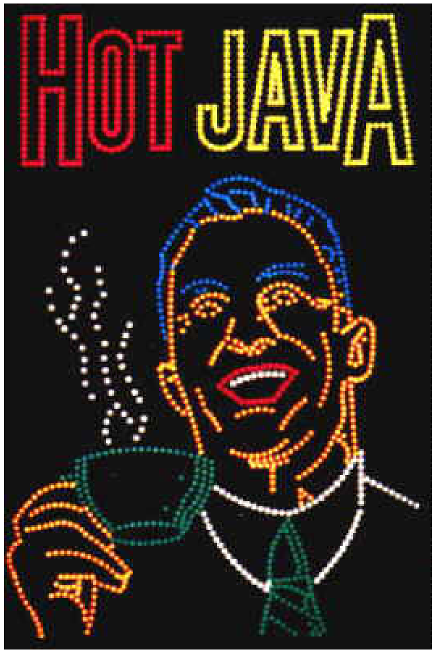
Lecture Outline

- ❒ Introduction
  - ❒ Classification
  - ❒ Fabrication
  - ❒ Packaging
- ❒ Fiber Impairments
- ❒ Fiber-Optic Communications
  - ❒ Point-to-Point
  - ❒ Networks
- ❒ Specialty Fibers
- ❒ Discussions

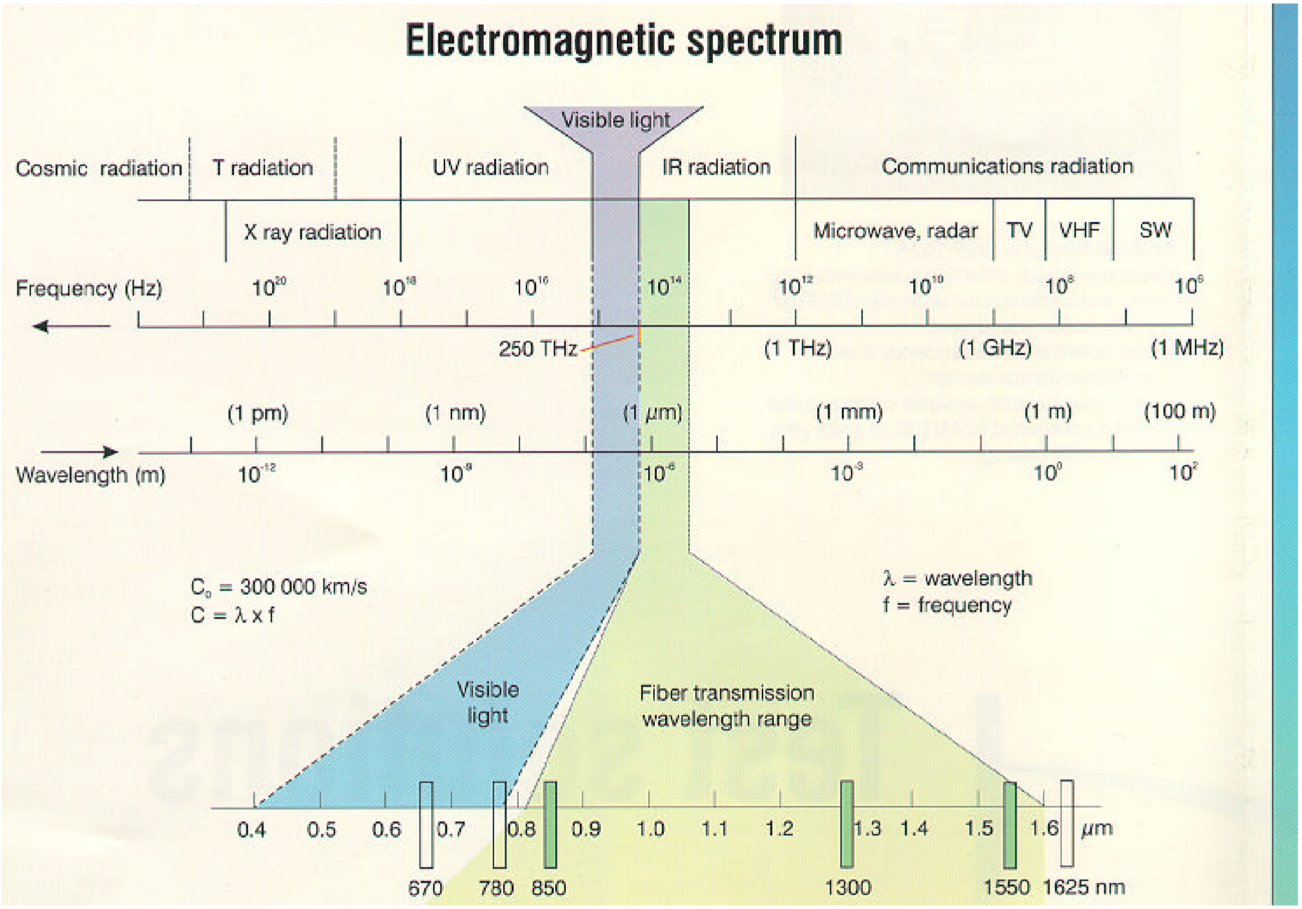
1. Introduction

- Fibers are waveguides for transporting light (beams) signals
- Application in a wide range of fields
  - Voice, visual & data Communications
  - Remote Sensing
    - Detecting, measuring & characterizing electromagnetic (EM) energy coming from distant objects
    - Geologic, agriculture, land use, meteorology etc.
    - This EM maybe collected and transported on fibers
  - Fiber-optic displays (e.g. speed-limit signs on motorways)
    - Cheaper to operate than neon lights
    - No annoying flickering or buzz noise (no interference from other EM sources)
    - Safe and withstands extreme weather conditions



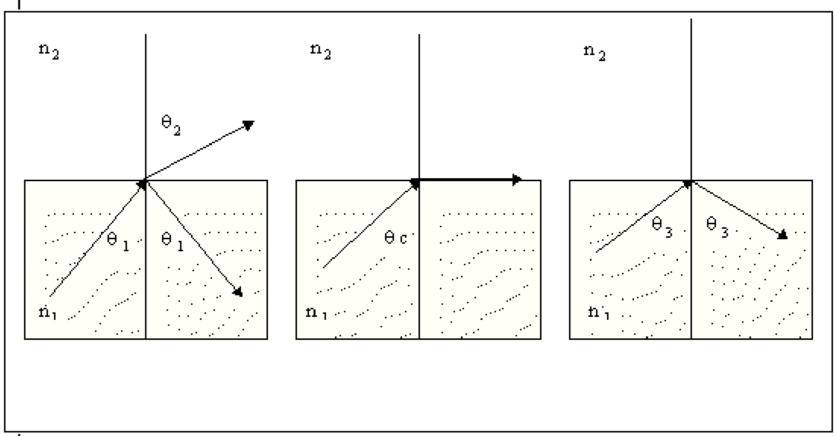
1. Introduction

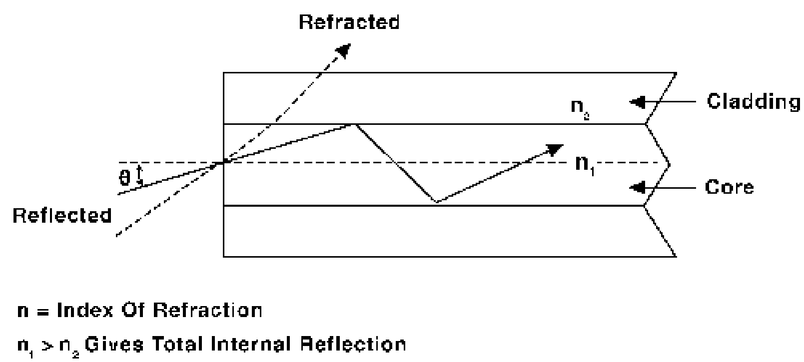
- Signals transmitted on fibers are within the infrared region of the EM spectrum



1. Introduction

- An optical fiber consists of two different types of highly pure, solid glass:
  - core
  - cladding
- Lightwaves are guided to the other end of the fiber by being reflected within the core (total internal reflection)
- The refractive index of the core is higher than the cladding
- In this way, the fiber core acts as a waveguide for the transmitted light by





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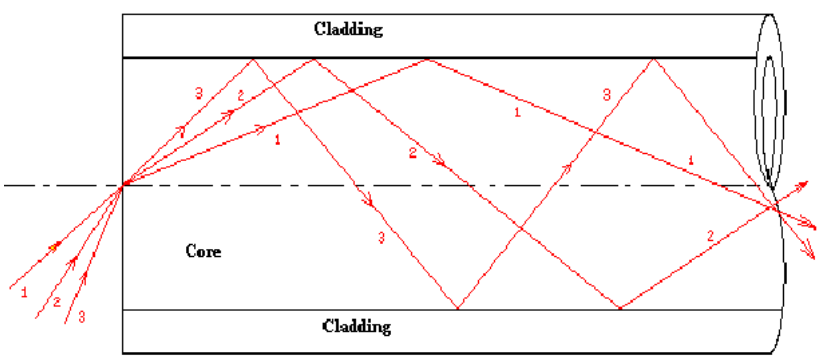
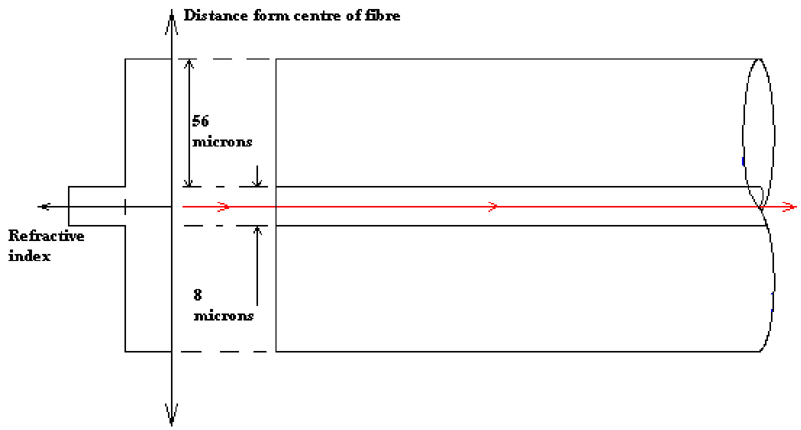
1.1 Fiber Types

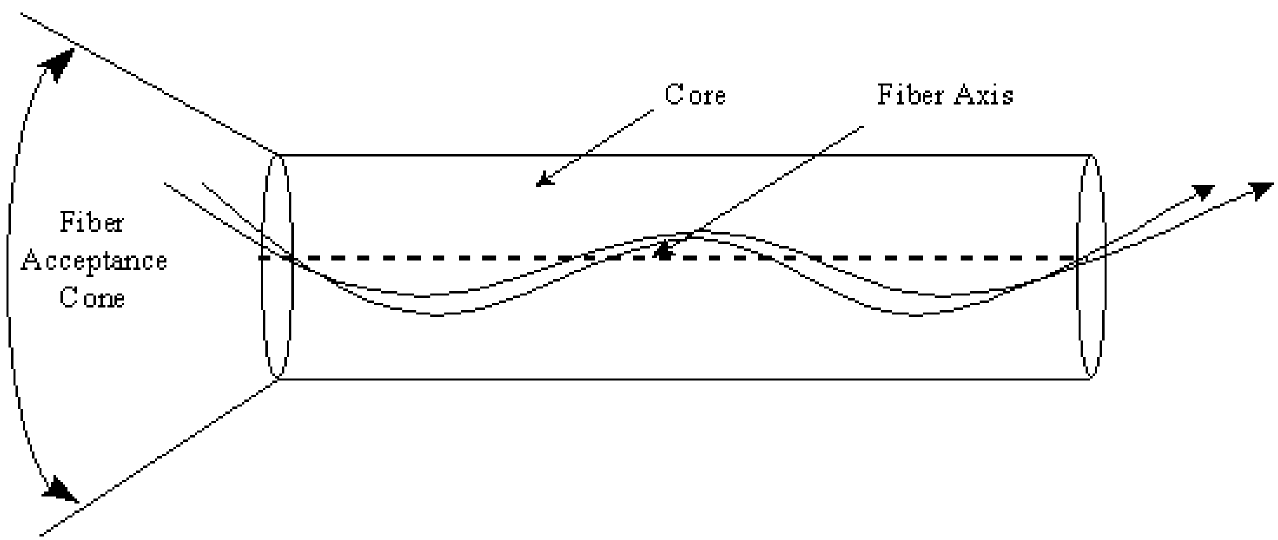
- There are two main fiber types:
  - Step index (multimode, single mode)
    - Step index fiber is so called because the refractive index of the fiber 'steps" up as we move from the cladding to the core of the fiber
    - Certain ray directions can actually travel down the fiber. These are called the "Fiber Mode"
    - In a multimode fiber many different modes are supported by the fiber. This is shown in the diagram below
    - Because its core is so narrow Single Mode Fiber (SMF) can support only one mode. This is called the "Lowest Order Mode"





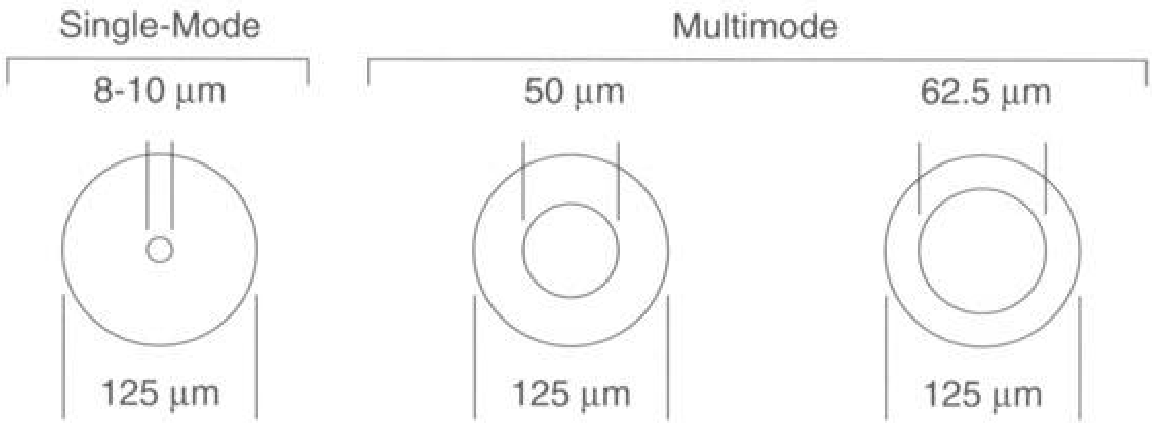
1.1 Fiber Types

- Graded index (multimode)
  - Has a different core structure from single mode and multimode fiber
  - In a graded index fiber the value of the refractive index changes from the centre of the core onwards (also called a Quadratic Profile)
  - The refractive index of the core is proportional to the square of the distance from the centre of the fiber
    - No cladding
  - Is actually a multimode fiber because it can support more than one fiber mode
  - The gradient in the refractive index gradually bends the rays back towards the axis



1.1 Fiber Types

- The international standard for the cladding diameter of optical fibers is 125 microns (µm)
  - This compatibility is important in that it allows fibers to fit into standard connectors and splices
- The differences among fibers lie in their core sizes
  - Standard Singlemode fibers are manufactured with the smallest core size, approximately 8-10 µm in diameter
  - For multimode fibers, the most widely used sizes are 50 µm and 62.5 µm.
  - Larger core sizes are easier to couple and interconnect.



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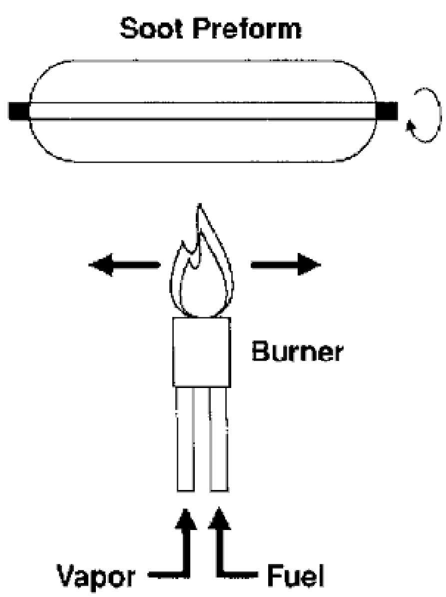
1.2 Fabrication

- Optical fiber manufacturing consists of three primary steps: laydown, consolidation, and draw
  - In the laydown step
    - A soot preform is made from ultrapure vapors as they travel through a traversing burner and react in the flame to form fine soot particles of silica and germania
    - These particles are deposited on the surface of a rotating target rod.
    - The core material is deposited first, followed by the pure silica cladding.



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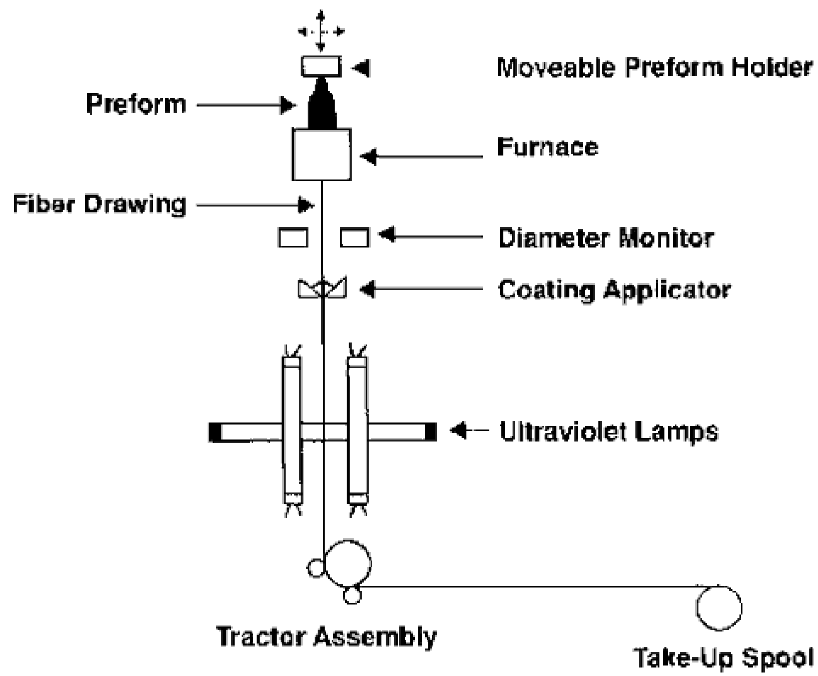
1.2 Fabrication

- Consolidation Step
  - When deposition is complete, the target rod is removed from the center of the porous preform, and the preform is placed into a consolidation furnace
  - The water vapor is removed from the preform
  - This high-temperature consolidation step sinters the preform into a solid, dense, and transparent glass.

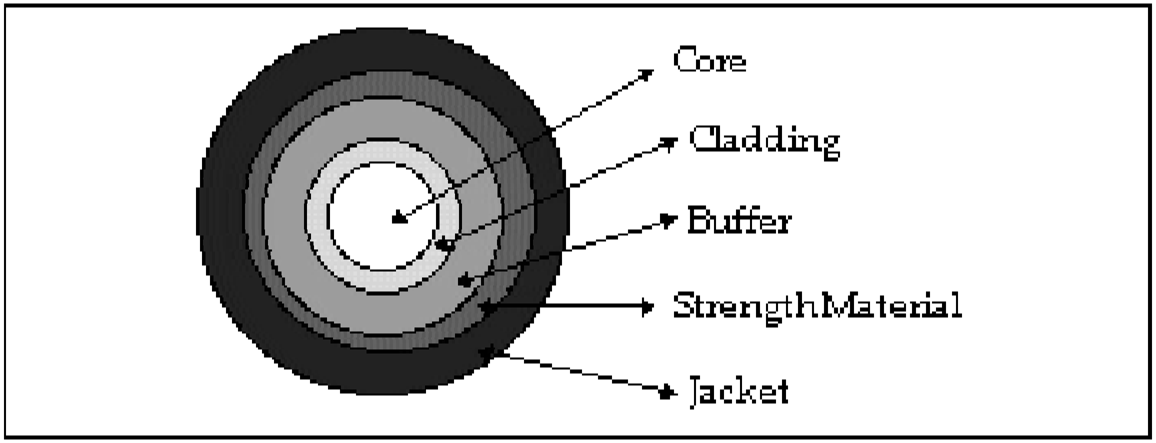


1.2 Fabrication

- The finished glass preform is placed in a draw tower and drawn into a continuous strand of glass fiber
- Fiber on these spools is
  - proof-tested to ensure the strength of each fiber,
  - cut to length,
  - and measured for performance of relevant optical and geometrical parameters

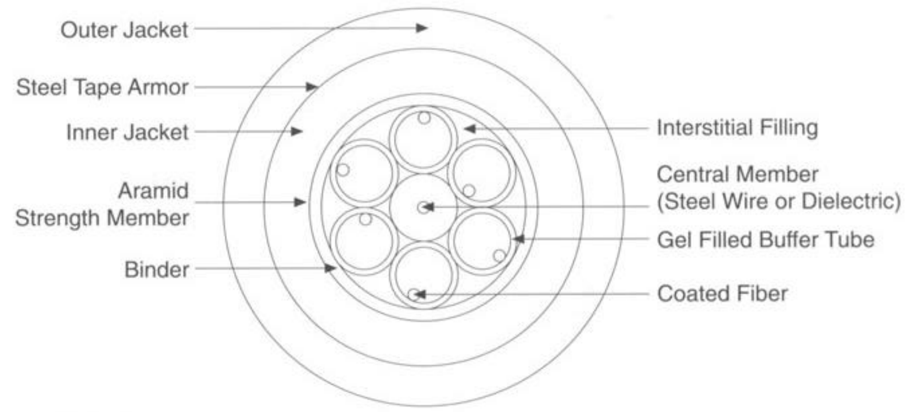
1.3 Cable Packaging

- There are generally five elements that make up the construction of a fiber-optic strand or cable:
  - The core ⇒ the optic core is the light carrying element at the center of the optical fiber, commonly made from a combination of silica and germania
  - Optic cladding ⇒ made of pure silica
  - Buffer material ⇒ used to help shield the core and cladding from damage
  - Strength material ⇒ preventing stretch problems when the fiber cable is being pulled
  - Outer jacket ⇒ protect against abrasion, solvents, and other contaminants.



1.3 Cable Packaging

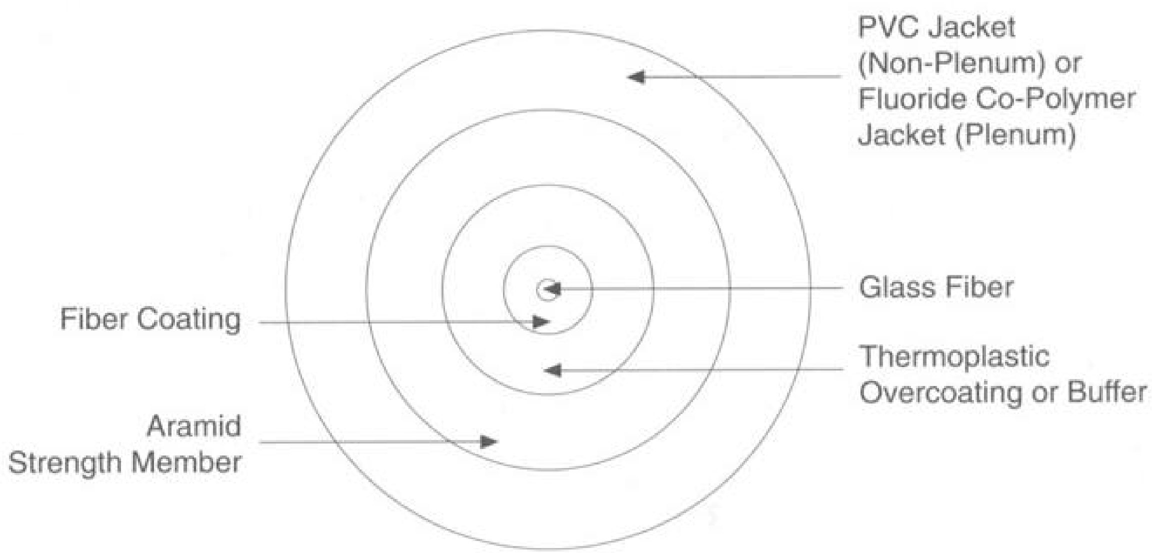
- Loose-tube cable,
  - used in the majority of outside-plant installations
  - Typically holds up to 12 fibers per buffer tube with a maximum per cable fiber count of more than 200 fibers.
  - Modular buffer-tube design permits easy drop-off of groups of fibers at intermediate points, without interfering with other protected buffer tubes being routed to other locations.
  - Design also helps in the identification and administration of fibers in the system.



Loose-Tube Cable

1.3 Cable Packaging

- Tight-tube cables
  - Primarily used inside buildings
  - Multi-fiber, tight-buffered cables often are used for intra-building and risers



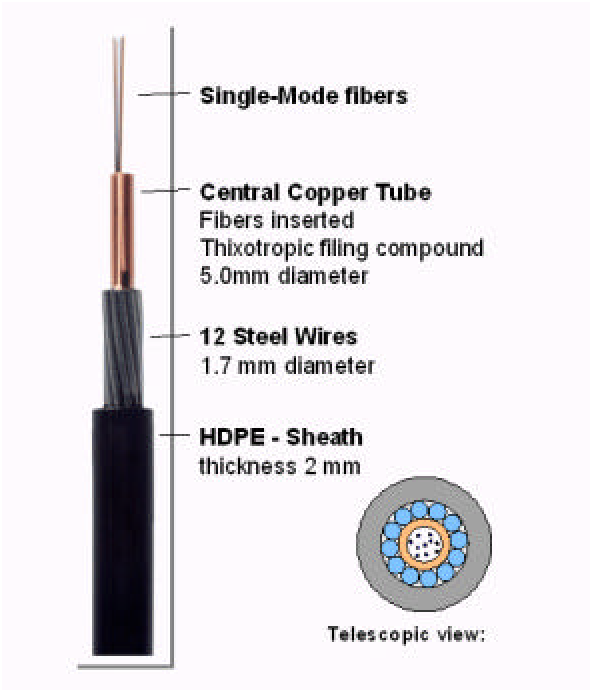
Tight-Buffered Cable

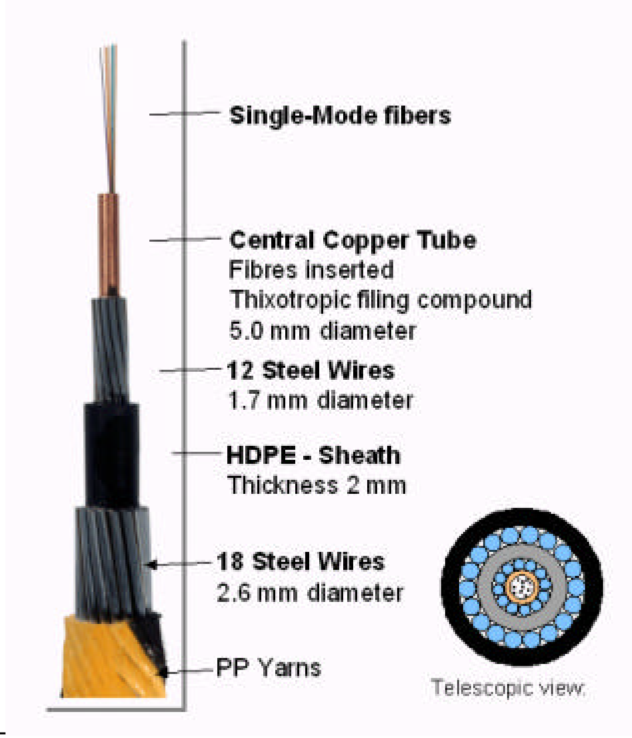
1.3 Cable Packaging

- Tactical (military) cables utilizes a tight buffer configuration in an all dielectric construction.
  - Tight buffer design offers increased ruggedness, ease of handling and connectorization.
  - Absence of metallic components
    - decreases the possibility of detection by enemies
    - minimizes system problems associated with electromagnetic interference.

1.3 Cable Packaging

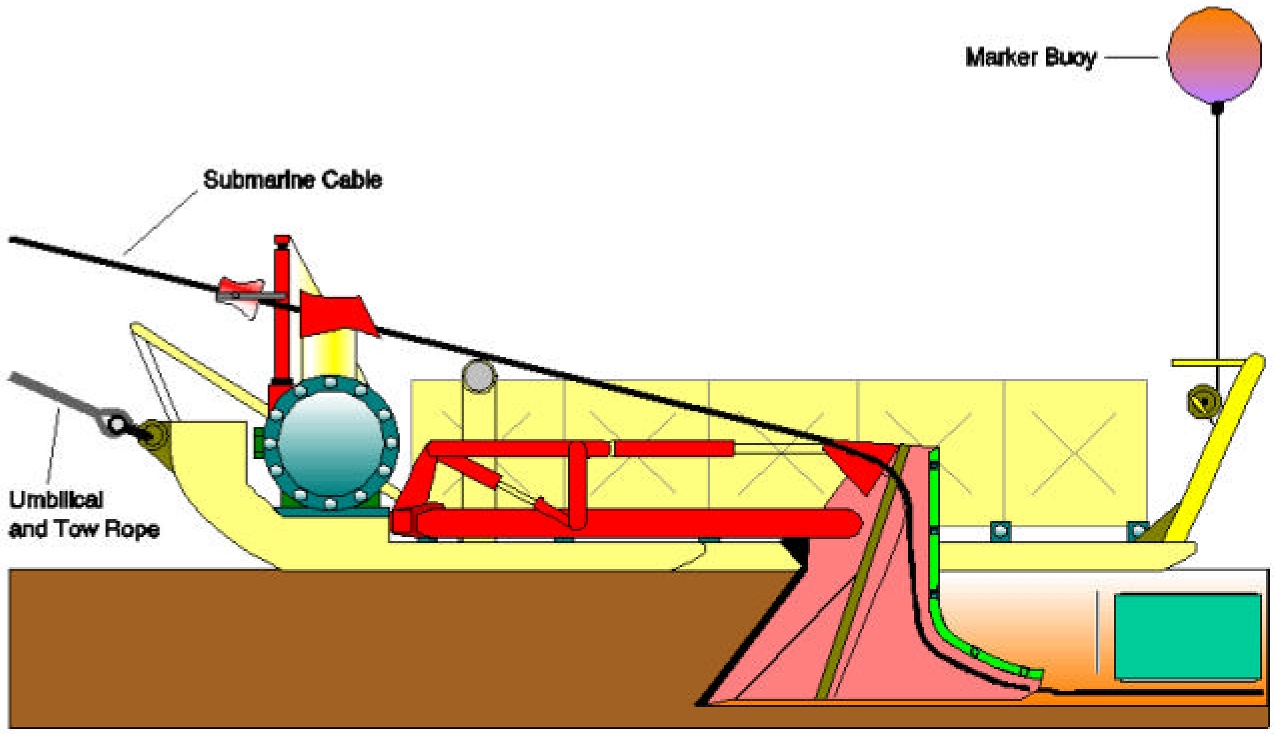
- Submarine (undersea) cables are more costly (20 \$ per metre-4 fibers)
  - Terrestrial cables (16-fiber tight-tube cables is 4 \$ per metre)
- More expensive to repair, therefore robustly designed
  - Tough light-weight single armoured cable for most routes
  - Heavier (> 500 kg/km) double-armoured cables for near shores/coasts





1.3 Cable Packaging

- Submarine cables laid by a ship towing a submarine cable plough
  - The plough digs the seabed 2 metres deep throughout the route
  - Laying of the cable is done simultaneously

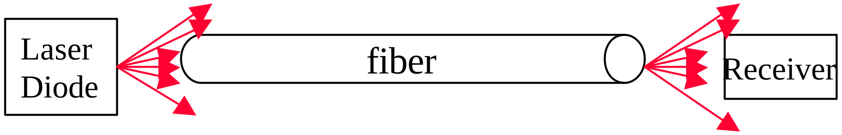


2. Fiber Impairments

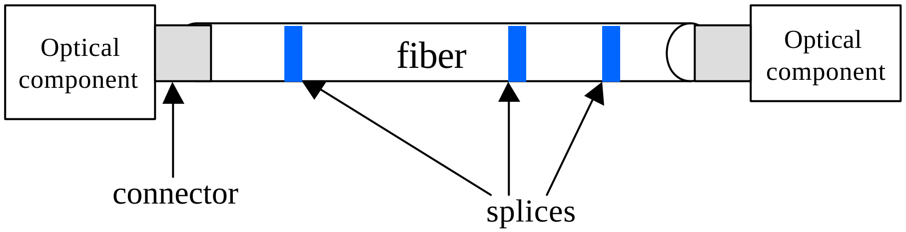
- Fiber waveguides exhibit three properties that cause impairment of a in communications
  - fiber attenuation
  - fiber dispersion
  - fiber nonlinear effects

2.1 fiber Attenuation

- Signal transmitted over fiber link has its power reduced by
  - Loss in transferring light from source-to-fiber and fiber-to-receiver



  - Connector (typically 0.5 dB) and splice losses (around 0.1 dB)



2.1 fiber Attenuation

- fiber loss, with attenuation coefficient being

$$a\left(\text{dB/km}\right) = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

where L is fiber length

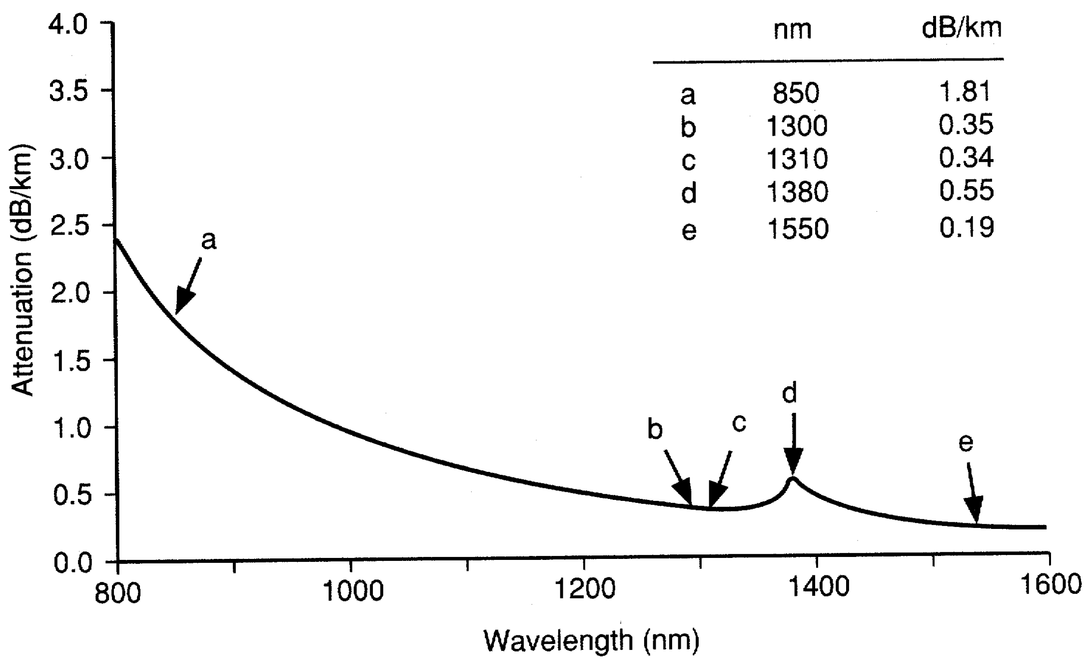


Fig. Attenuation characteristics of a standard single-mode fibers (SMF)

2.1 fiber Attenuation

- Improvements in attenuation at 1.4 μm obtained by removing OH^- ions
  - Example is Lucent's AllWave fiber
- This provide a transmission window of over 200 nm

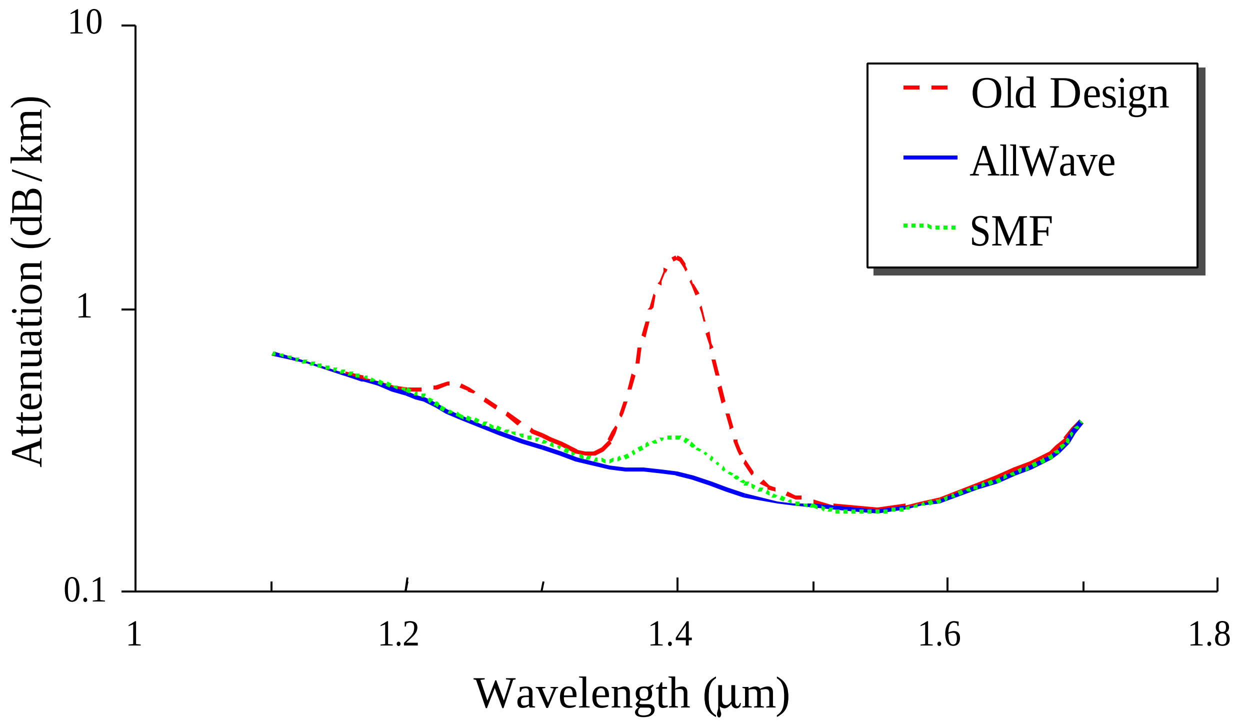
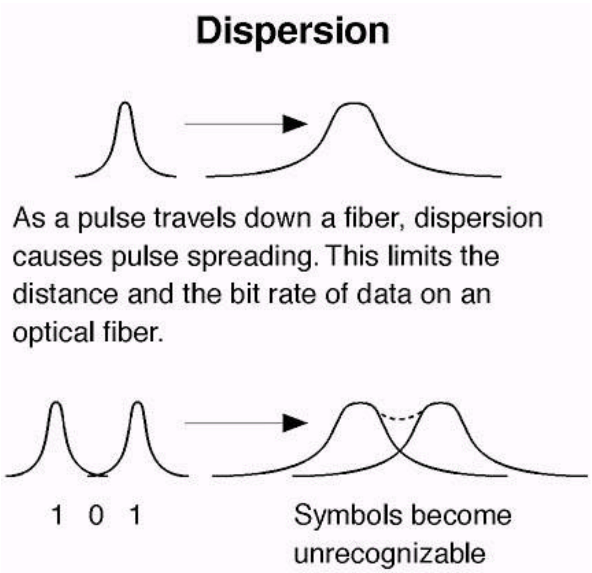


Fig. Singlemode fiber attenaution improvements

2.2 Dispersion

- Dispersion causes pulse smearing (hence intersymbol interference)
- Chromatic dispersion is the most damaging mechanism, consists of
  - Waveguide dispersion ⇒ Wavelength-dependent power distribution between core and cladding
  - Material dispersion ⇒ Index of refraction is dependent upon wavelength, therefore different wavelengths will travel down an optical fiber at different velocities



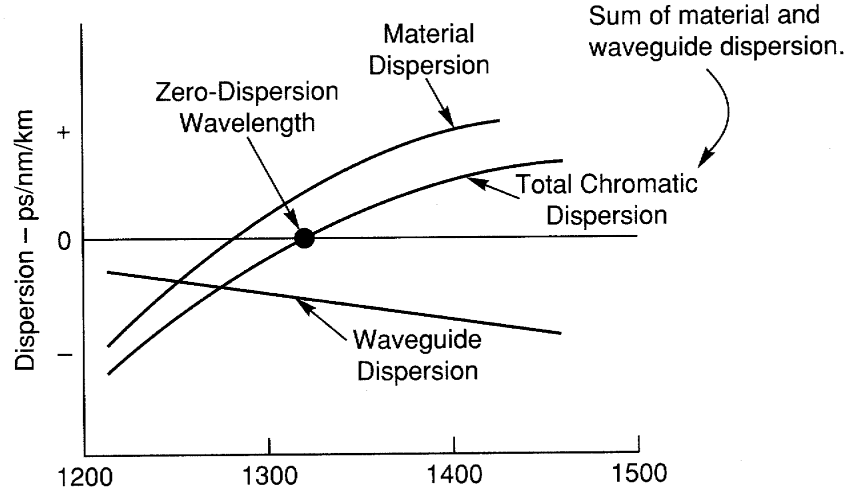


Fig. Chromatic dispersion in standard single-mode fibers

2.2 Dispersion

- Others include
  - modal dispersion : significant only for multimode fibers.
  - polarization mode dispersion (PMD): only significant for very long distance fiber links

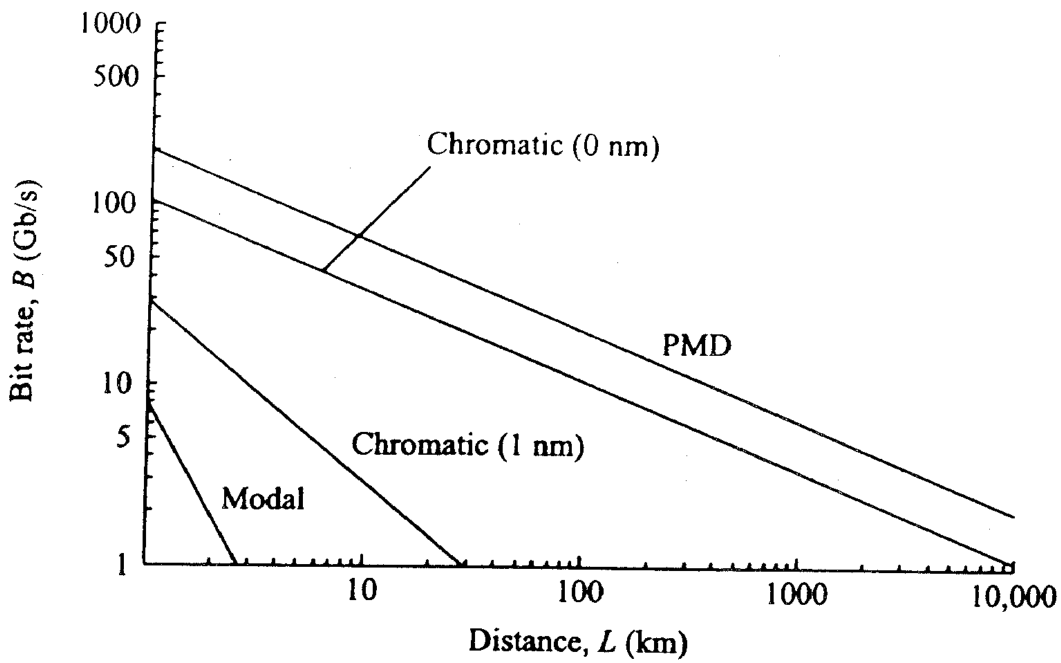


Fig. Distance and bit rate limits due to dispersion. Source spectral widths of 0 and 1 nm considered for chromatic dispersion

2.2 Dispersion

- Dispersion reduction solutions
  - Using dispersion shifted fiber (DSF) with the design altered to shift the zero dispersion wavelength to 1550nm
  - Using dispersion compensating fiber (DCF) with a negative dispersion slope at each amplifier location

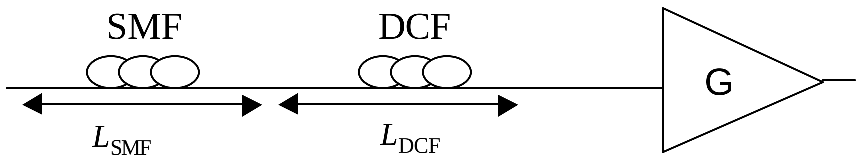


Fig. Dispersion Compensation using DCF

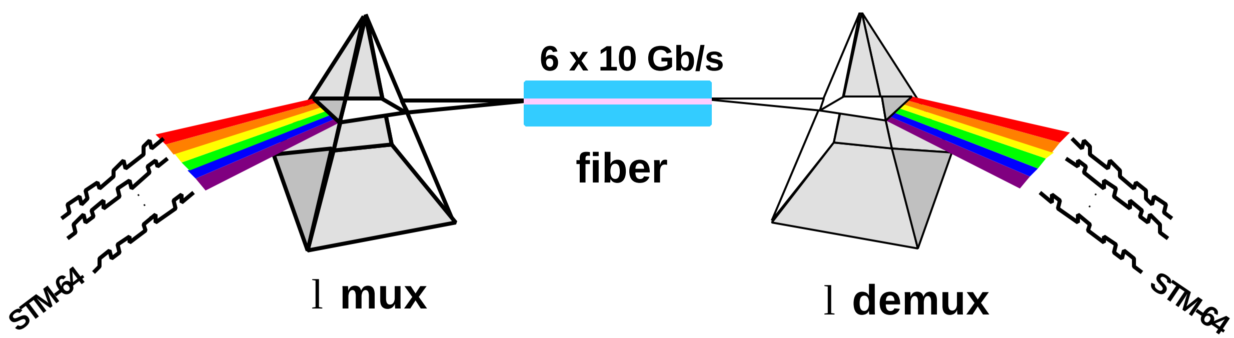
$$L_{DCF} = \frac{L_{SMF} \cdot D_{SMF}}{\left| -D_{DCF} \right|}$$

$$G = L_{SMF} \cdot a_{SMF} + L_{DCF} \cdot a_{DCF}$$

Where D_{SMF} and D_{DCF} are the dispersion coefficient of the SMF and DCF fibers

2.2 Dispersion

- Wavelength-division multiplexing (WDM) is basically a multiplexing technique in the optical domain
  - Enables the combination of a number of wavelength channels (or optical frequencies) onto a single fiber link,
- It is essentially frequency division multiplexing (FDM) at optical carrier frequencies (~ hundreds of THz),



Wavelength Division Multiplexing (WDM)

2.2 Dispersion

- Dispersion varies for each channel
  - In WDM (multi-channel) systems, its difficult to compensate all channels using a common DCF
  - Alternative would be to demultiplex and perform compensation for each channel individually

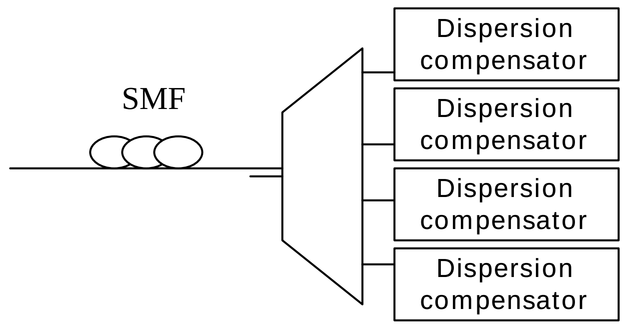


Fig. Dispersion compensation of WDM systems

2.3 Fiber Nonlinearities

- With increased optical power levels, fibers exhibit nonlinear effects due to scattering effects and refractive index variation of fiber medium
- This nonlinear behaviour of fibers can place some limitations on communication system design
- The nonlinear effects include
  - Stimulated Brillouin Scattering (SBS)
  - Stimulated Raman Scattering (SRS)
  - Four Wave Mixing (FWM)
  - Self-Phase Modulation (SPM)
  - Cross-Phase Modulation (CPM)
- SBS, SRS and FWM effects provide gain to some channels at the expense of depleting power from some other channels
- The longer the link length the more the interactions and the worse the effects of nonlinearities

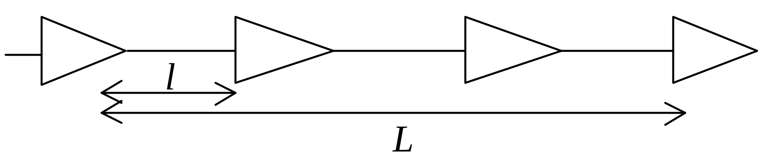
2.3 Fiber Nonlinearities

- To model the effects of nonlinearities a model is used that assumes the power is constant over a certain “effective length” L_e

$$L_e = \frac{1 - e^{-aL}}{a}$$

where is α the attenuation coefficient and L is the actual link length

- In amplified systems, effective length is sum of effective length of each span



$$L_e = \frac{1 - e^{-aL}}{a} \frac{L}{l}$$

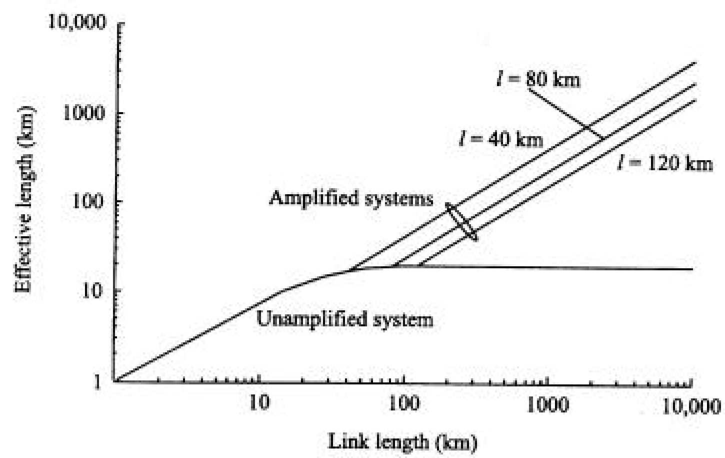


Fig. Effective transmission length as a function of link length

2.3 Fiber Nonlinearities

- Similarly, since power is not uniformly distributed in cross-section of a fiber, we use effective cross-sectional area A_e
  - This is related to cross-section intensity distribution $I(r, \theta)$

$$A_e = \frac{\left[\int_r \int_q r\,dr\,dq\,I(r,q) \right]^2}{\int_r \int_q r\,dr\,dq\,I^2(r,q)}$$

where r and q are the polar co-ordinates

- The power level at which the effects of nonlinearity becomes significant is known as the threshold power
  - One should transmit signal below threshold power

2.3.1 Stimulated Brillouin Scattering

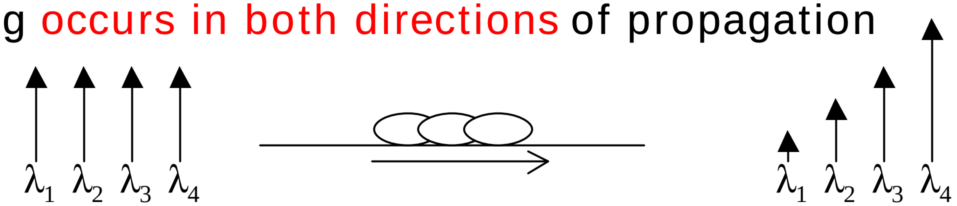
- SBS doesn't cause interaction for channel spacing >> 20 MHz
- Distorts signal by producing backwards gain (towards source)
- The SBS is characterised by a approximate gain coefficient $g_B = 4 \times 10^{-11}$ m/W at all wavelengths
- Assuming a narrow source linewidth, the threshold power due to SBS is

$$P_{\mathrm{th}} = \frac{21 b A_e}{g_B L_e}$$

where *b* is a polarisation dependent constant lying between 1 and 2 depending

2.3.2 Stimulated Raman Scattering

- SRS causes power to be transferred from lower to higher wavelength channels
  - Its characteristic gain coefficient is dependent on wavelength spacing ($\Delta\lambda_s$)
  - Peak at 1.55μm is g_R=6 x 10-14 m/W
- Coupling occurs in both directions of propagation



- For a system of W equally spaced wavelength channels, the power coupled from channel *0* to other channels is

$$P_0=\sum_{i=1}^{W-1}P_0(i)=\frac{g_R\Delta l_s P L_e}{2\Delta l_c A_e}\frac{W(W-1)}{2}$$

where $\Delta\lambda_c$ is the Raman gain bandwidth (between 80 and 120 nm)

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2.3.2 Stimulated Raman Scattering

- Assuming that there is only negligible dispersion in the system, the threshold power is

$$P_{th} = \frac{4 \cdot 10^4}{L_e (W-1) \Delta l_s}$$

- With dispersion the threshold power is doubled!

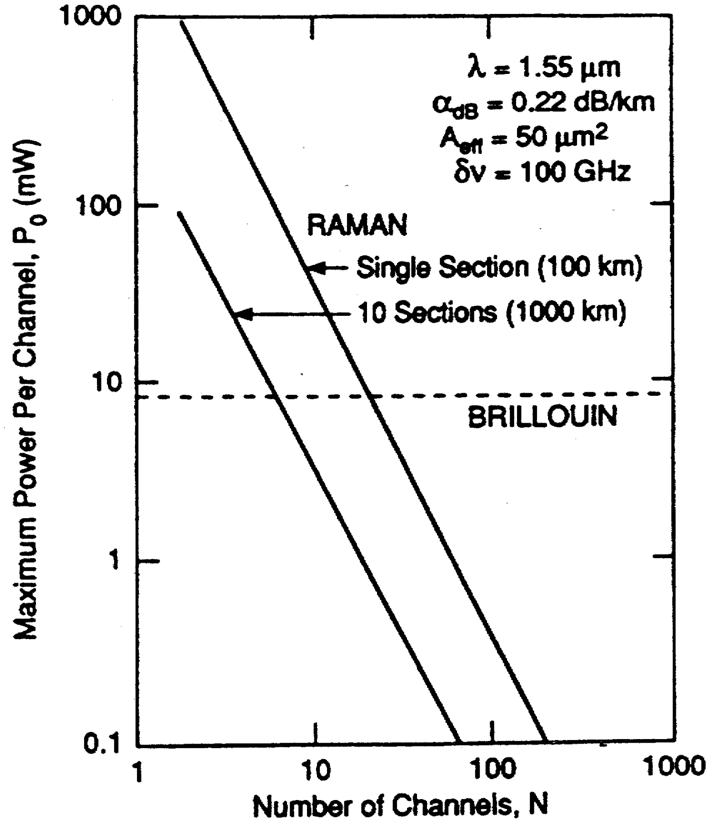


Fig. Power limitations due to SRS and SBS for a WDM system. Channel spacing δν is assumed to be 100 GHz

2.3.3 Four-Wave Mixing

- Signals at three frequencies w_i , w_j and w_k combine to produce signals which include a damaging signal at frequency

$$w_{ijk} = w_i + w_j - w_k, i \neq j, \ \ j \neq k$$

  - This signal may interfere with one of the existing signals

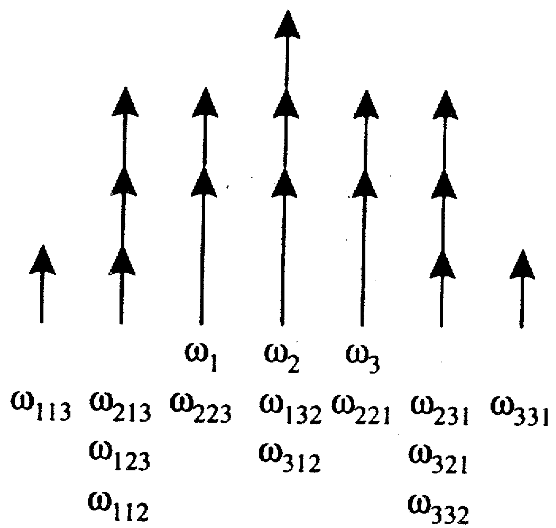


Fig. FWM terms caused by beating between w_i , w_j and w_k

2.3.3 Four-Wave Mixing

- Unfortunately FWM efficiency is enhanced by the lack of dispersion and/or narrow channel spacing
  - This is more significant for WDM systems using DSF (D ≈ 0 ps/nm-km)
  - Not a major problem with SMF (D ≈ 17 ps/nm-km)
  - Necessitated the development of non-zero dispersion shifted fibers (NZDSF) that compensates for dispersion & avoids FWM (D between 1-6 ps/nm-km)

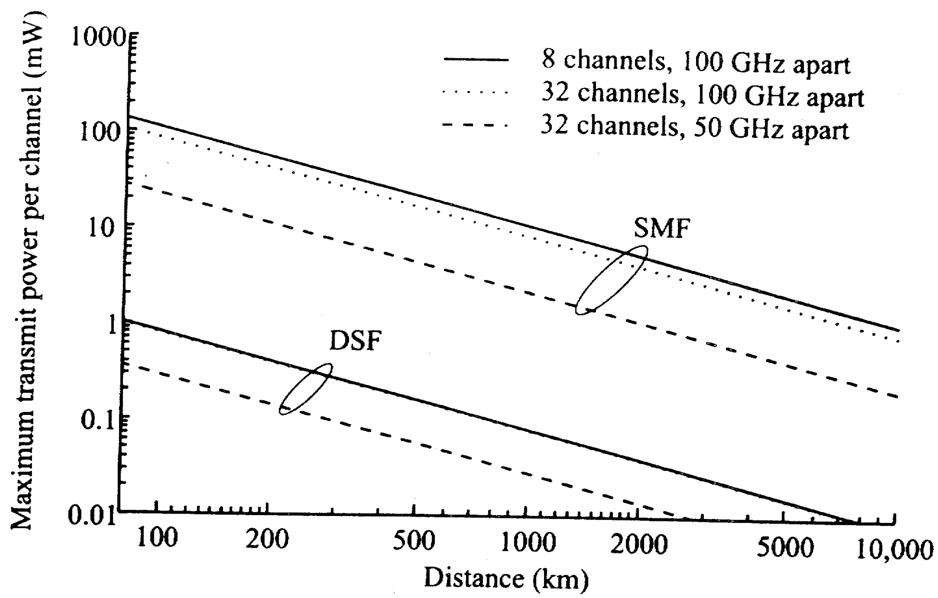


Fig. Limitation on the maximum power per channel due to FWM

2.3.4 Self- and Cross-phase Modulation

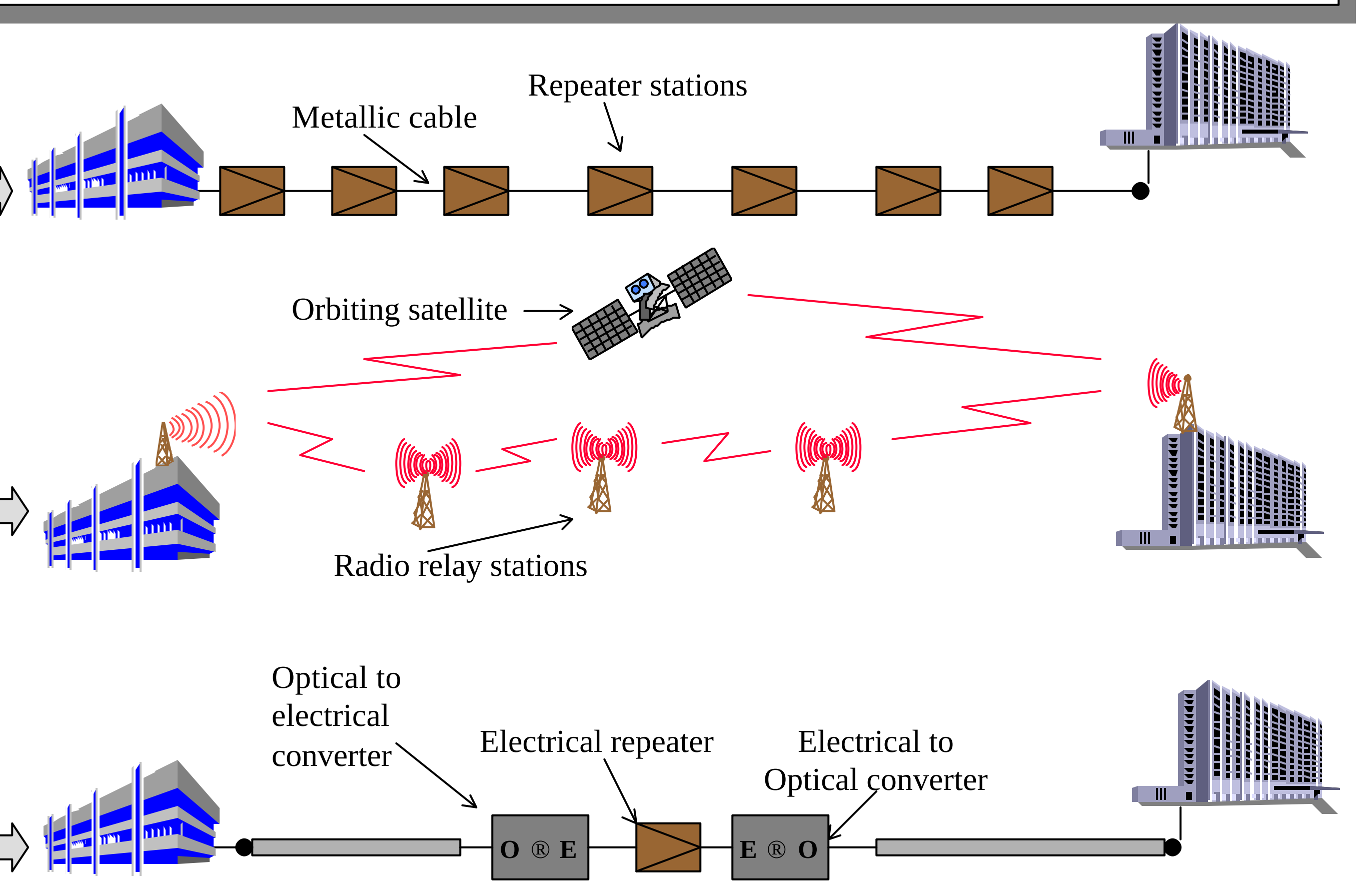
- Fluctuations in optical power causes changes in phase of the signal
  - leads to higher dispersion penalties
  - Self phase modulation (SPM): converts power fluctuations in a propagating channel to phase fluctuations in the same wavelength channel
    - limits maximum power per channel
    - SPM only significant systems designed to operate at >10 Gb/s
  - Cross phase modulation (XPM): converts power fluctuations in a propagating channel to phase fluctuations in co-propagating wavelength channels
    - limits the possible reduction in channel spacing
    - CPM considered for WDM systems with channel spacing < 20 GHz

3. Fiber-Optic Communications

- Twisted copper pairs
- Coaxial cables

- Terrestrial radio links
- Microwave relay
- Satellite links

- Early optical fiber links

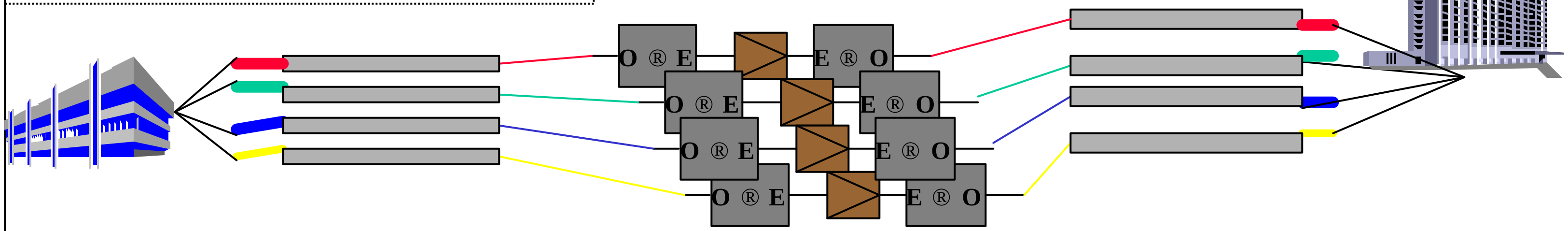


Transmission loss⇓ Capacity⇑ Size&weight⇓

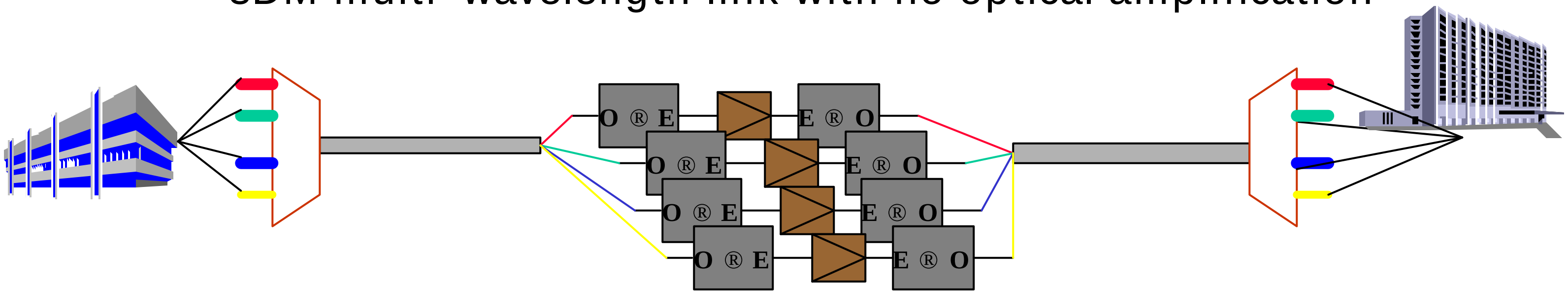
Immunity to electromagnetic interference⇑ Security level⇑

3.1 Fiber Links

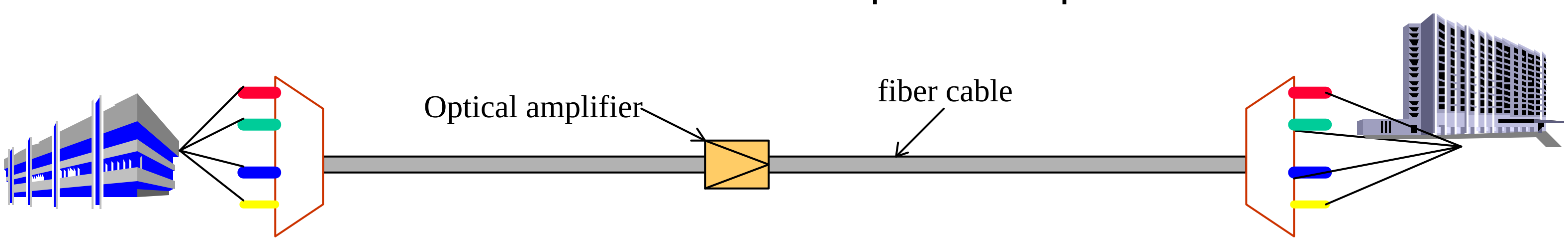
λ_1 = red; λ_2 = green; λ_3 = blue; λ_4 = yellow;



SDM multi-wavelength link with no optical amplification



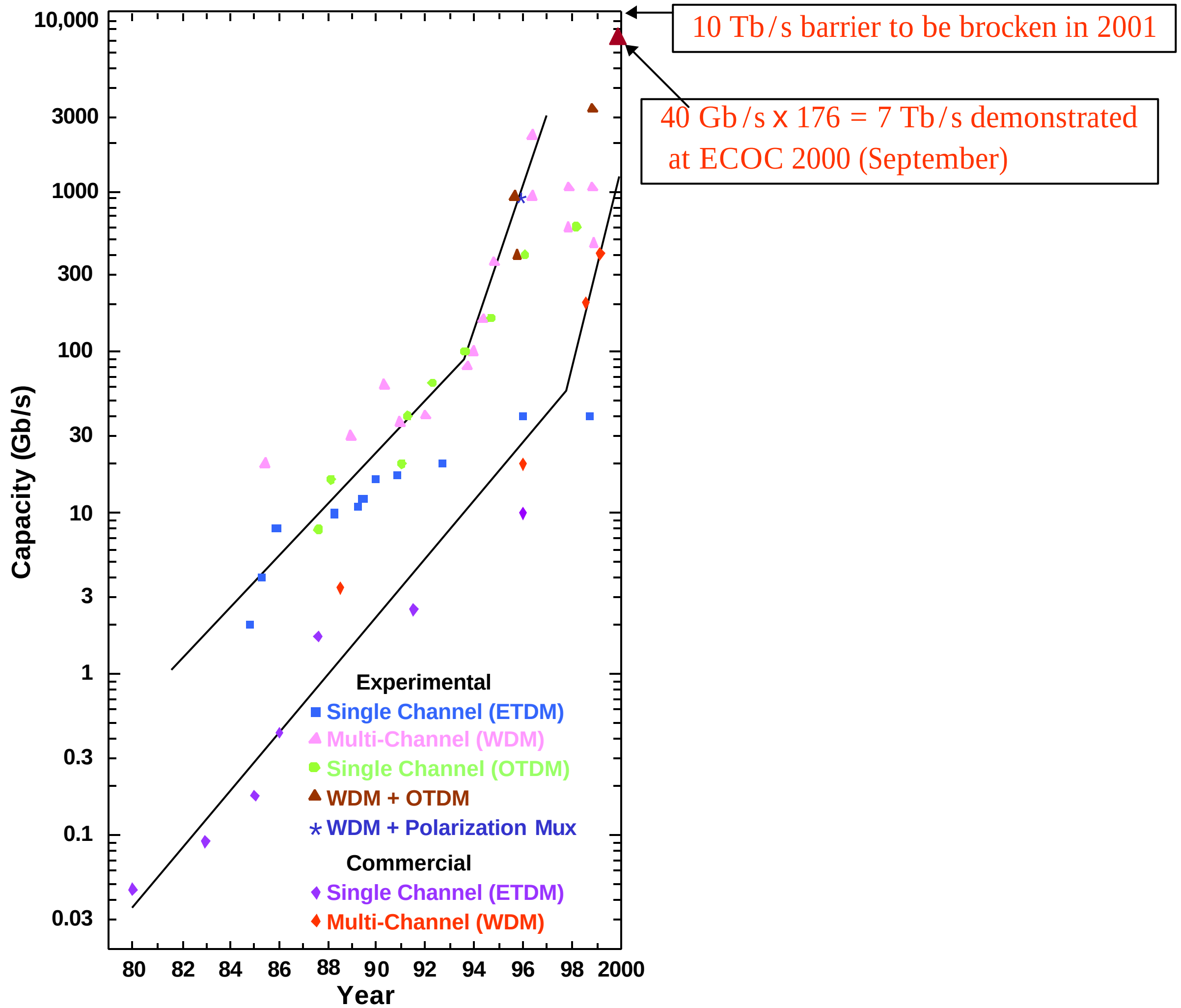
WDM fiber link with no optical amplification



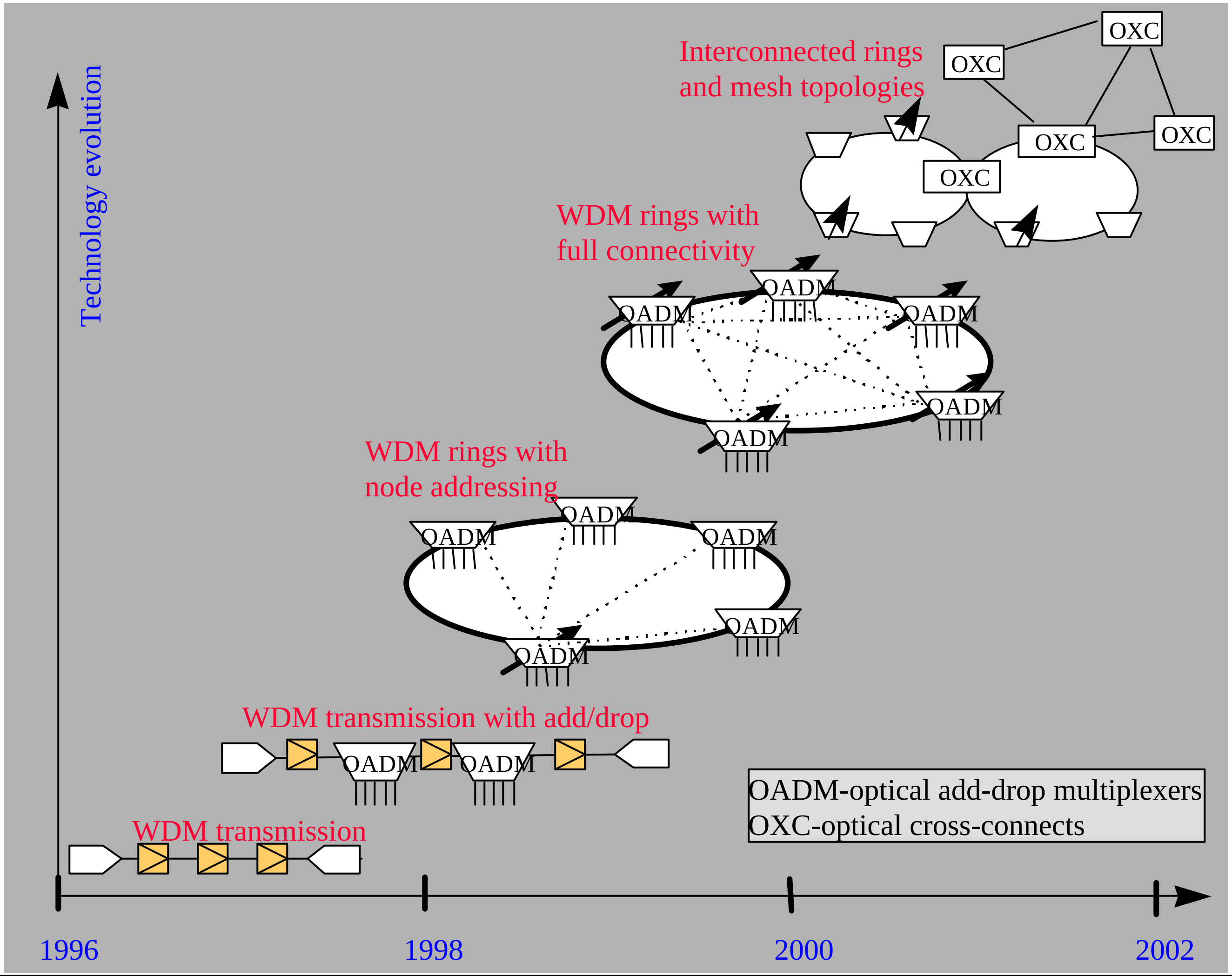
WDM fiber link with optical amplification

3.1 Fiber Links

- Alternative or hyrbid multiplexing schemes (OTDM, OCDM, OTDM-WDM)

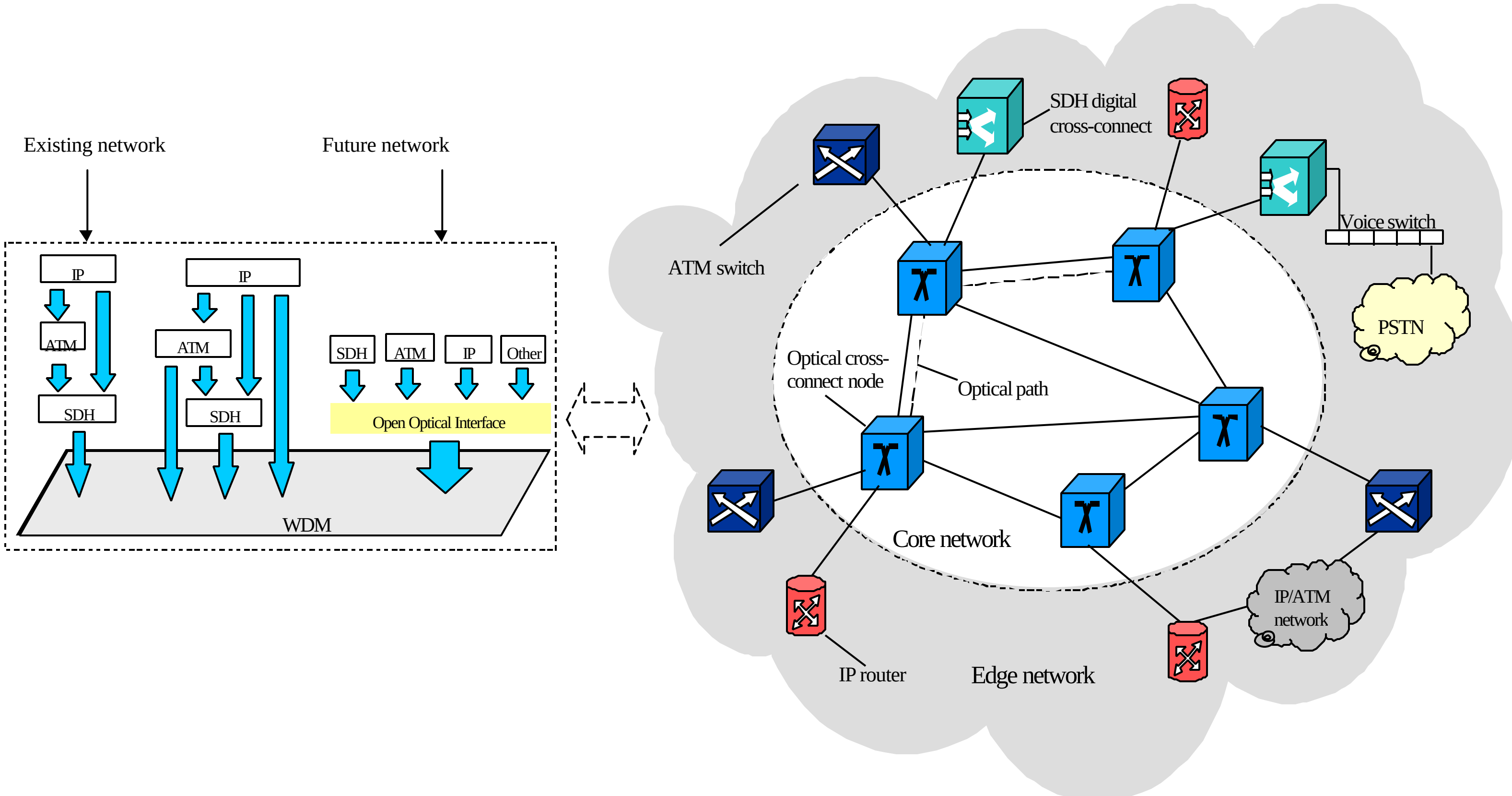


3.2 Transport Networks (MANs,WANs)



3.2 Transport Networks (MANs,WANs)

Everything over WDM

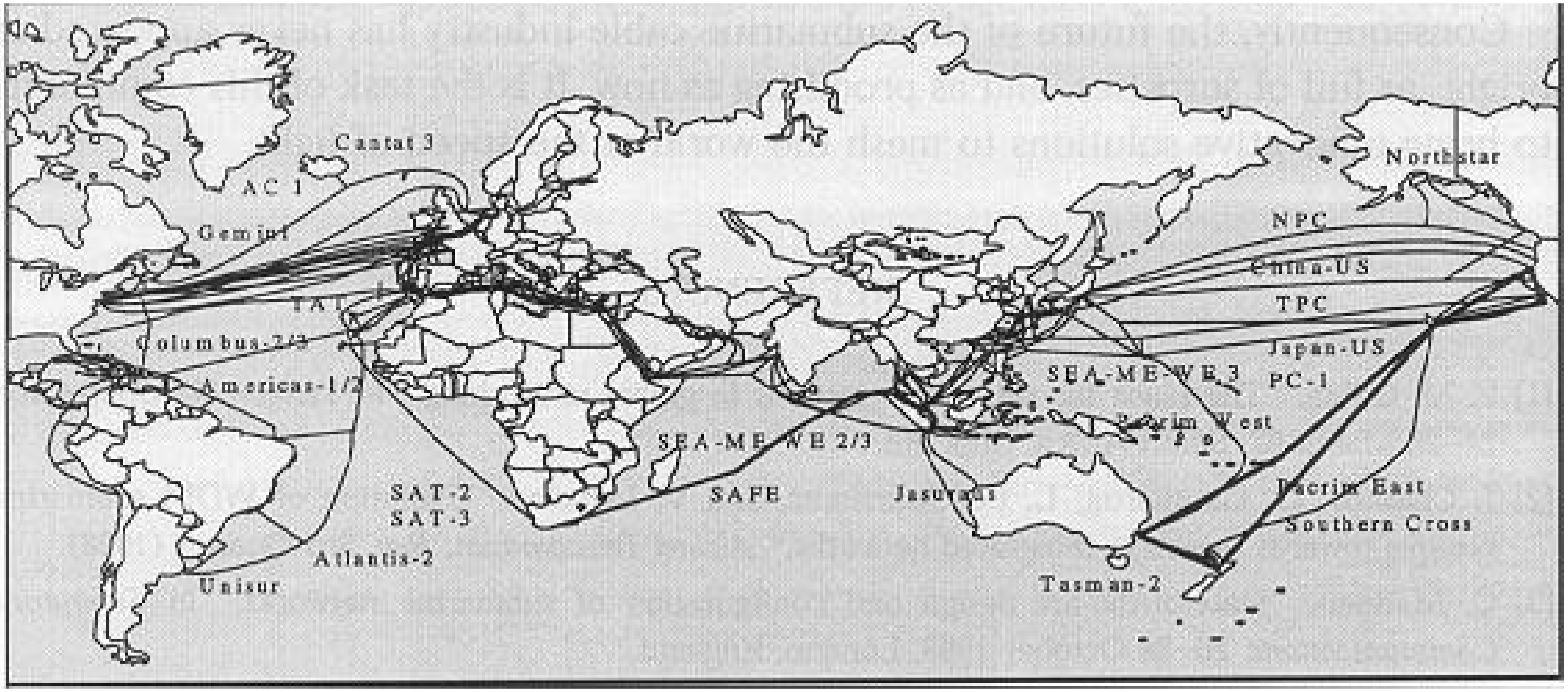


3.2 Transport Networks (MANs,WANs)

- Fibers are now deployed over various forms of the existing infrastructure
  - Now non-IT companies such as Power or Railway Companies own fiber plants
  - Leasing (or swapping) of dark fiber is a big business, extends coverage of new operators

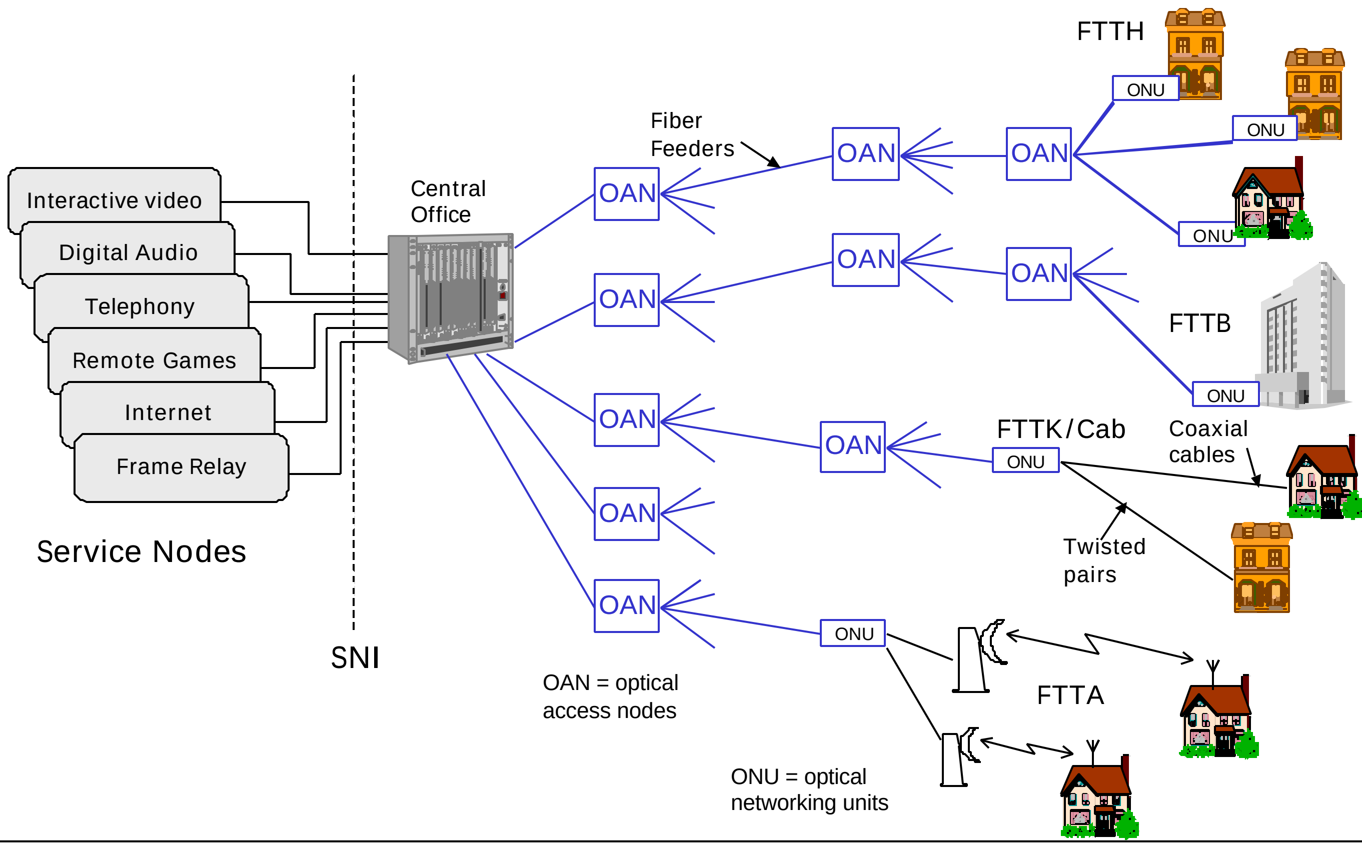
3.2 Transport Networks

- Submarine cables now carry much more inter-continental traffic than satellite systems
  - Trans-Atlantic Telephone 8 (TAT-8) is 1st fiber cable system, began operating 1988



3.3 Optical Access Networks

- Hub links with optical network units (ONUs) via optical access nodes (OANs)
  - For passive optical networks (PONs) ⇒ OANs are just passive splitters or combiners
  - Expensive to lay fibers to the home (about US$ per home passed)
  - Use cheap alternatives like plastic optical fibers and techniques suc as air-blown fibers

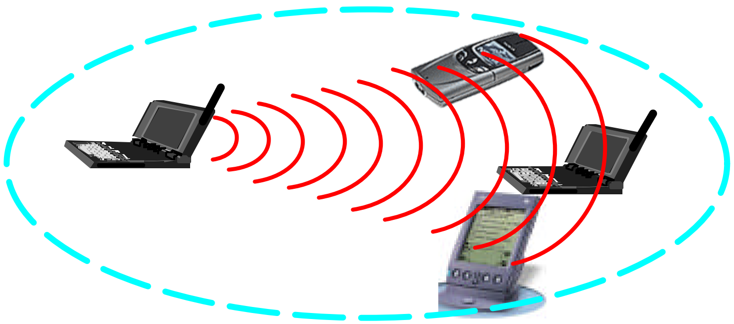


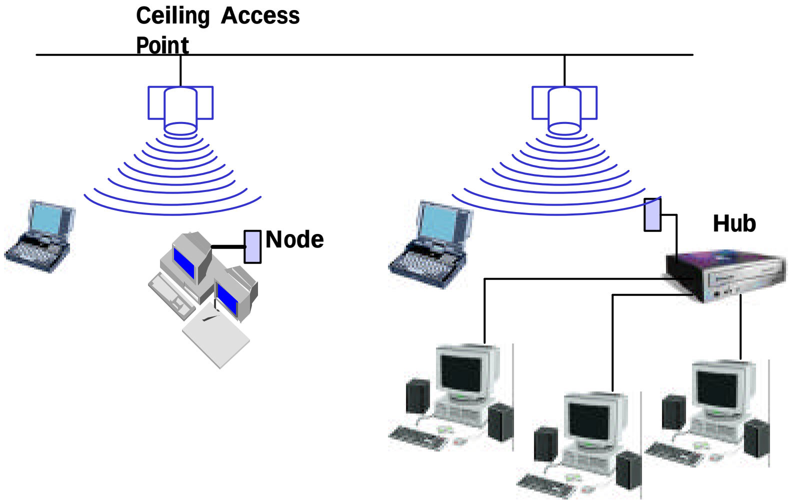
3.3 Optical Access Networks

- Future local area networks (company or campus networks) boosted by Gigabit Ethernet
  - Offers 1 Gbit/s both ways
  - Uses the 802.3 Ethernet Frame Format
  - Uses CSMA/CD access method
  - Backward compatible with 10Base-T and 100Base-T technologies
- Following cables could be used for Gigabit Ethernet
  - Cat 5 unshielded twisted pairs (UTP) for about 100 m
  - Multimode fibers (50 µm) for links up to 550 m at 1300 nm
  - Singlemode fibers for 3 km at 1300 nm

3.4 Infrared Links

- So far main focus has been on development of indoor systems (coverage limited to a few meters)
  - Inter-connection of printers, laptops, PDAs (point-and-shoot)
  - Camera-monitor connectivity of CCTV applications,
  - Infrared wireless LAN applications (e.g. 10 Mb/s systems like VIPSLAN & iRLan)





3.4 Infrared Links

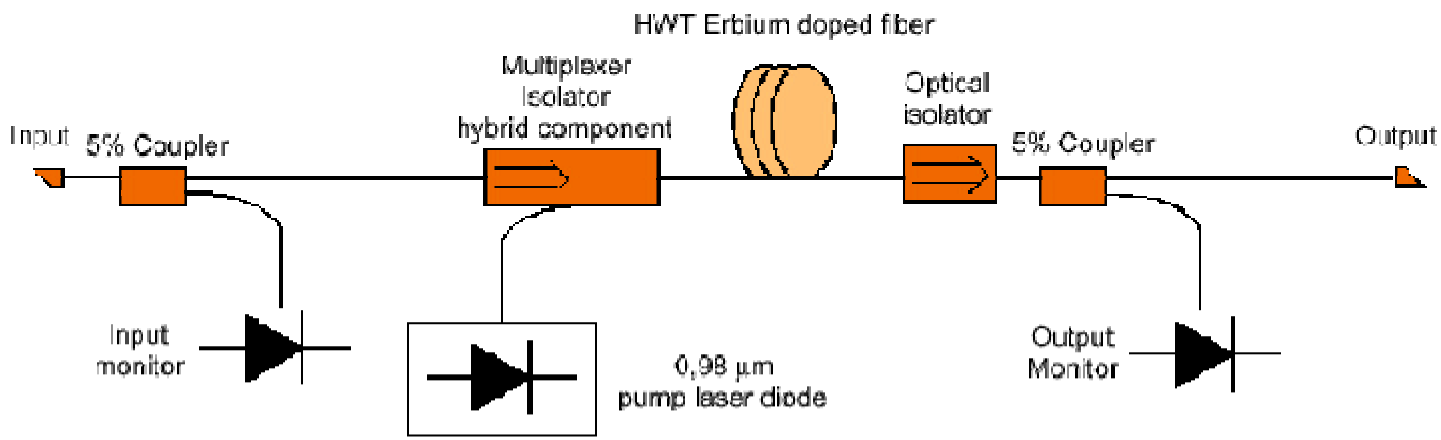
- Point-to-point outdoor systems for LAN interconnection
  - Example includes Jolt UWIN 4400 (155 Mbit/s)

Link attenuation and the weather

	Attenuation (dB/km)	Maximum range in m of Jolt UWIN 4400 system
Clear weather	3	6000
Rain (30 mm/hr)	10	2500
Cloudburst (100 mm/hr)	17	1800
Moderate snow	17	1800
Blizzard	30	1100
Light fog	30	1100
Moderate fog	50	800
Thick fog	100	450
Clouds	300	200

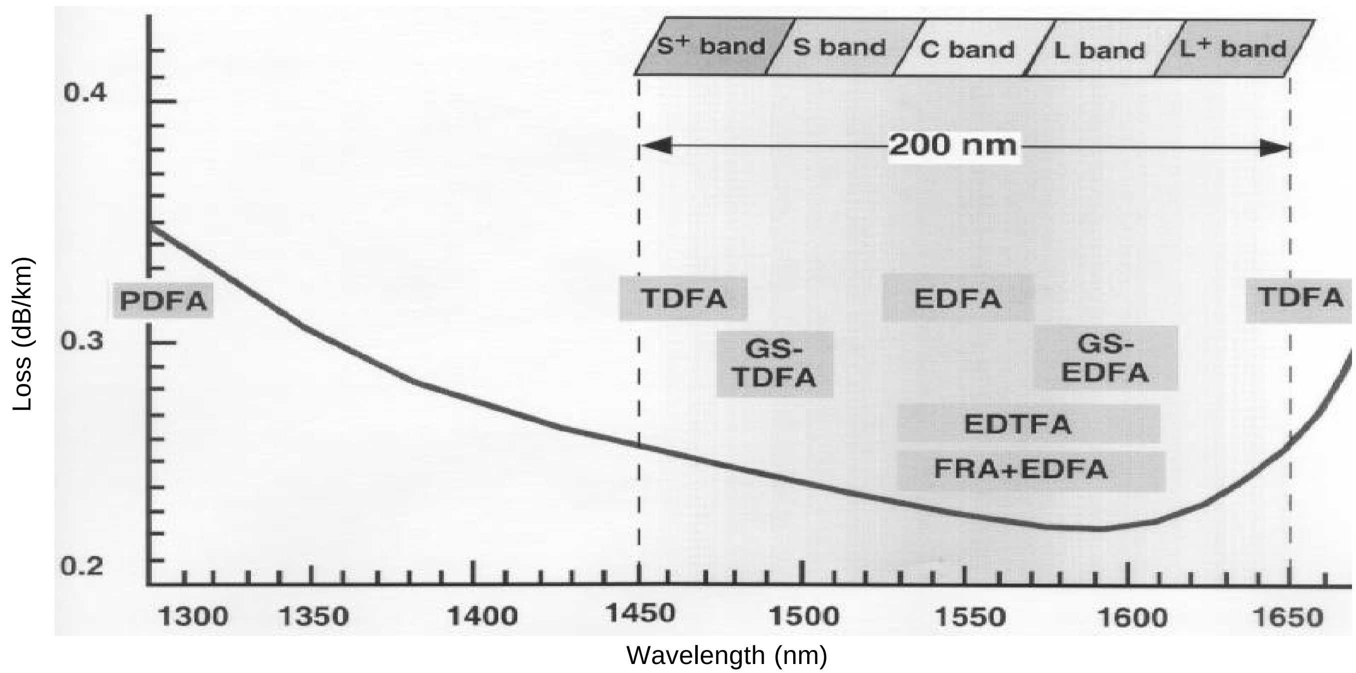
3.5 Specialty Fibers

- Fiber that perform additional function(s) apart from just acting as ”light pipes”
  - Fiber devices made from fibers
- The erbium doped fiber amplifier (EDFA) is the most popular example
  - Amplifies WDM signals (G about 20 dB) in the 1530-1560 nm window



3.5 Specialty Fibers

- Altering the host (amplifying pece of fiber) or dopant materials results in opening of more transmission window
- L-band (1560-1620 nm) amplifiers to be commercially available very soon.



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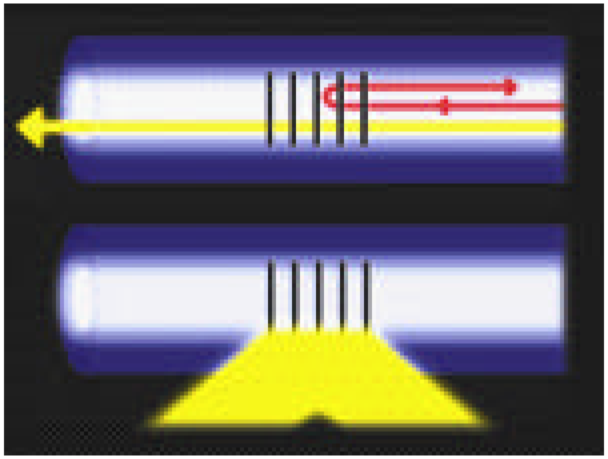
3.5 Specialty Fibers

- Fiber Bragg gratings (FBGs) another exciting development, used for
  - Optical filtering
  - Dispersion compensation
  - Flattening of EDFA gain spectrum
- FBG can also be tuned by varying the pattern (grating) period
  - Wavelength routing devices
  - Remote sensing



When the UV light passes through a phase mask, an interference pattern is produced creating a structural change in the core of the fiber resulting in a permanent and stable modification of its refractive index.

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4. Conslusions

- Fibers were covered from the basic aspects
  - Design, fabrication and cable packaging
- The possible impairments on a signal carried by a fiber waveguide
  - Attenuated and dispersed
  - Fiber nonlinearities, especially if WDM transmission is used
- Use of fibers in optical communications systems
  - Usable at all levels of the network: residential, business, metropolitan, national
  - Several km of fibers laid every minute!
  - Major role to play in all forms of communications

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