

EE1002: Part 2

Lecture 5



香港城市大學
City University of Hong Kong

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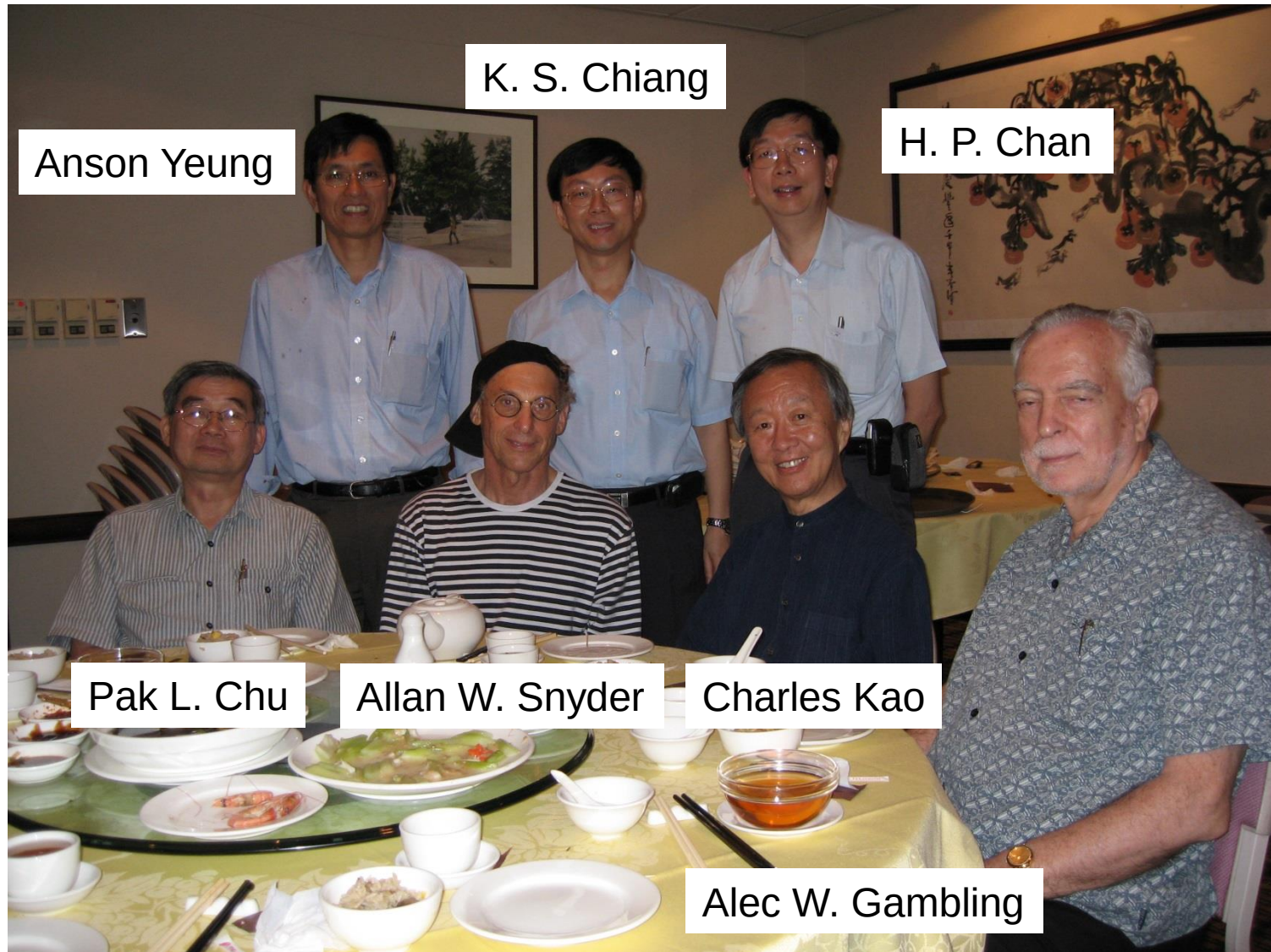
- Optical fibers
- Light transmission in a multimode fiber
- Light transmission in a single-mode fiber
- Wavelength-division multiplexing (WDM)
- Optical communication systems
- Local access networks

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Optical Fibers



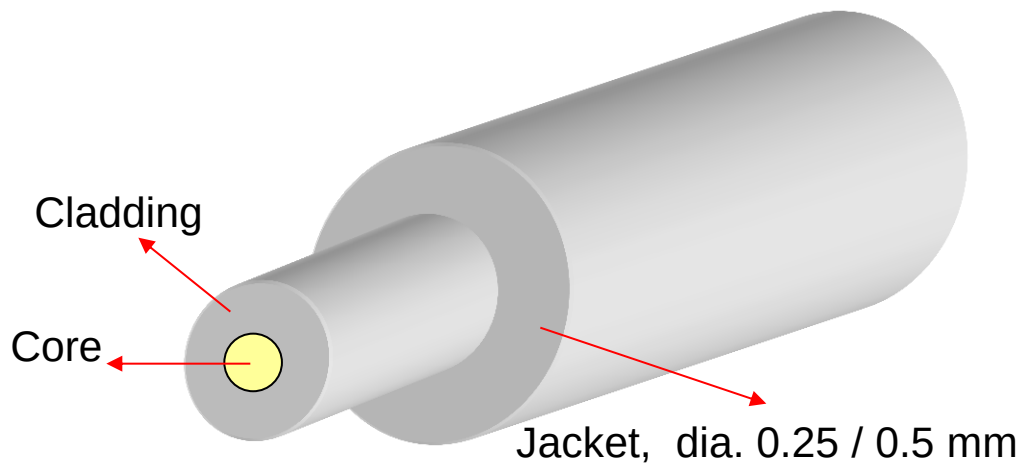
Charles K. Kao (高錕) received the Nobel Prize in Physics in 2009 “for groundbreaking achievements concerning the transmission of light in fibers for optical communication”.



City University of Hong Kong, 14 May 2006

Optical Fibers

An **optical fiber** is a flexible, transparent hair-thin fiber made of glass (silica) or plastic, which is mainly used as a means to transmit light.



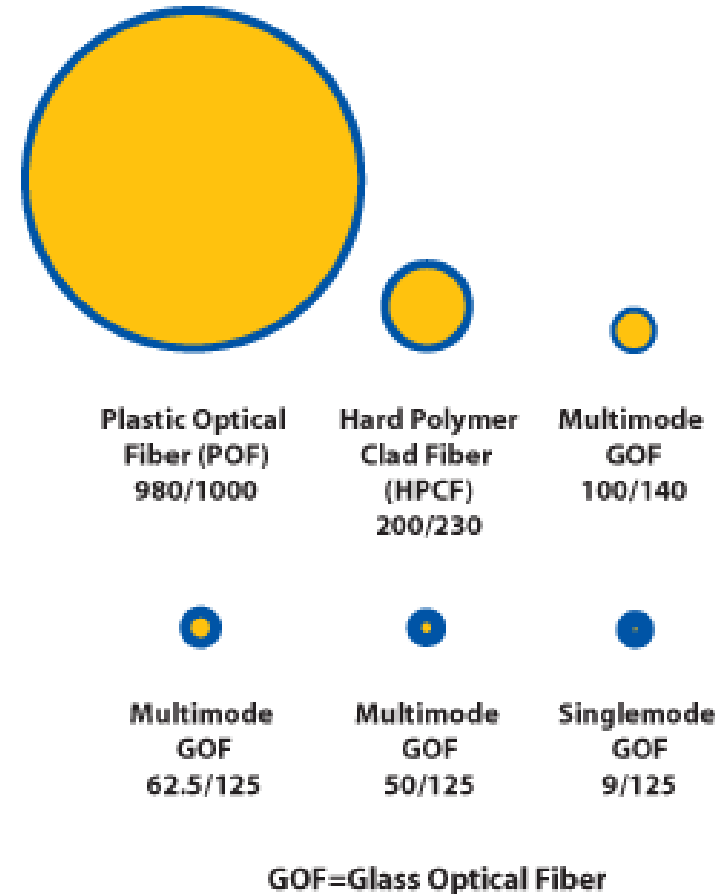
Multimode fiber

Glass fiber: Core dia.: 50 - 100 μm
Cladding dia.: 125 - 140 μm

Polymer fiber: Core dia.: ~ 1 mm

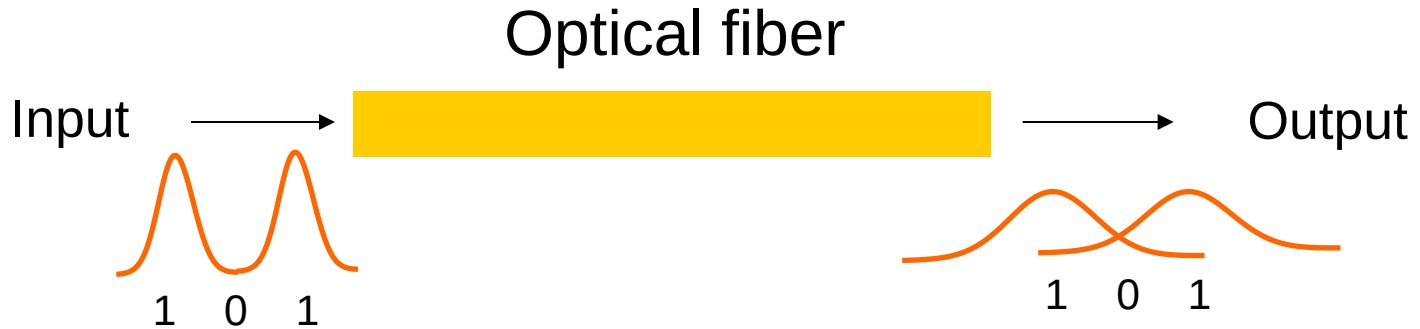
Single-mode fiber

Glass fiber: Core dia.: 8 - 10 μm
Cladding dia.: 125 μm



The refractive index of the core is higher than that of the cladding by $\sim 1\%$ ($\Delta \sim 1\%$)

Optical Fibers



The **signal-carrying capacity** of an optical fiber is characterized by the maximum number of pulses it can transmit per second, i.e., the maximum bit rate.

Fiber attenuation causes power loss and limits the transmission distance.

Fiber dispersion causes pulse broadening and limits the bit rate.

Note:

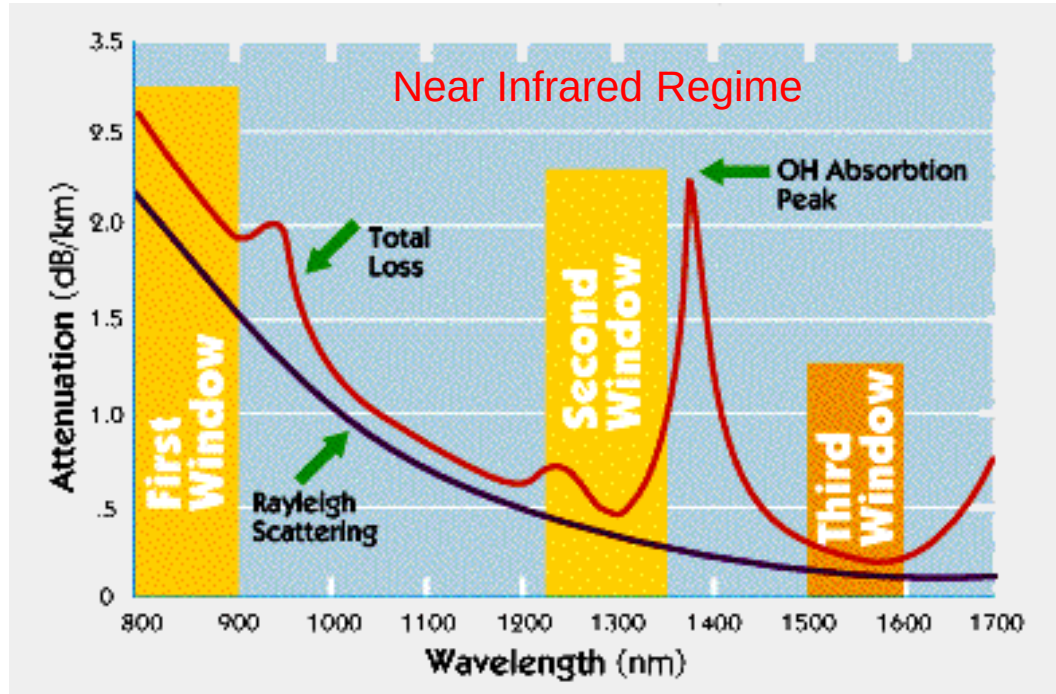
1 Mb/s = 10^6 pulses/second (a typical novel)

1 Gb/s = 10^9 pulses/second

1 Tb/s = 10^{12} pulses/second

Optical Fibers

Attenuation Spectrum of Silica (SiO_2)

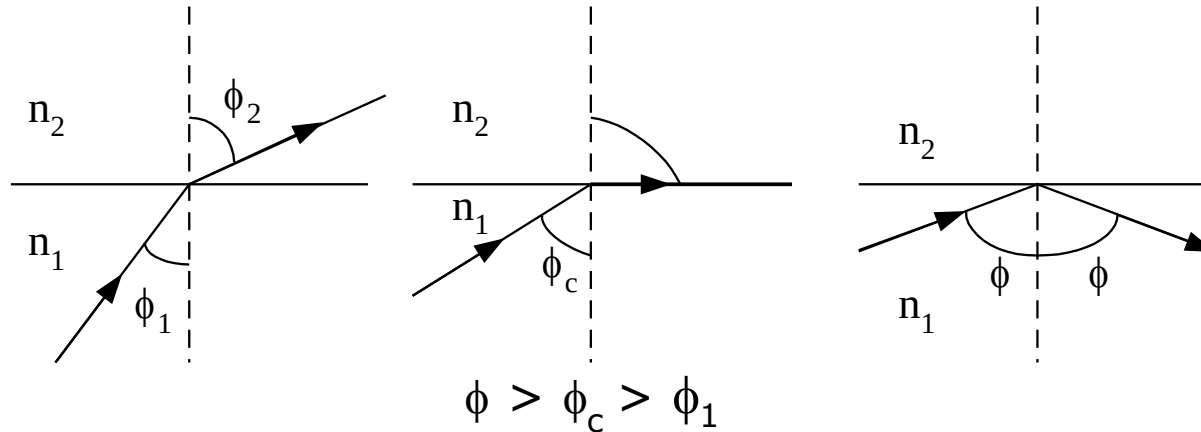


<http://www.vislab.usyd.edu.au/photonics/fibers>

The lowest loss 0.2 dB/km is achieved at the wavelength 1550 nm.

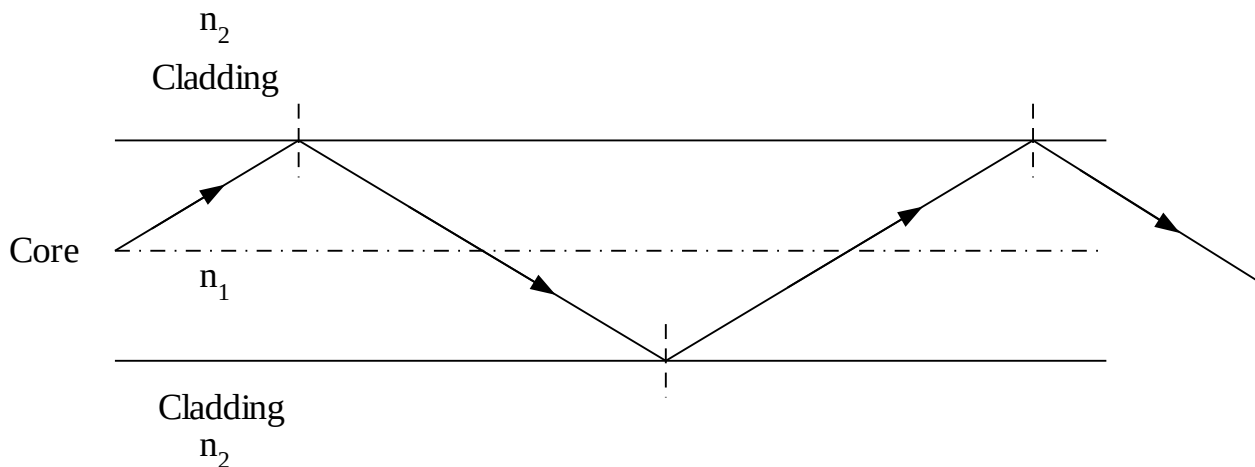
Polymer optical fiber has an attenuation coefficient varying from several tens to several hundreds dB/km, depending on the fiber material and the wavelength.

Total Internal Reflection

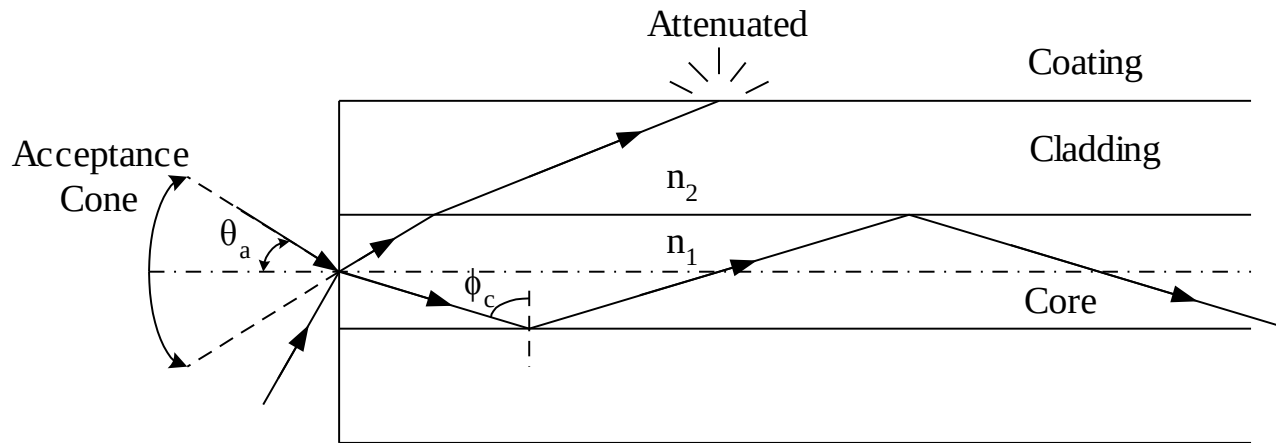


Snell's Law: $n_1 \sin \phi_1 = n_2 \sin \phi_2$ **Critical angle:** $\phi_c = \sin^{-1} \frac{n_2}{n_1}$

Transmission of a ray in a large-core **step-index fiber**



Maximum Acceptance Angle and Numerical Aperture



Maximum Acceptance Angle (θ_a)

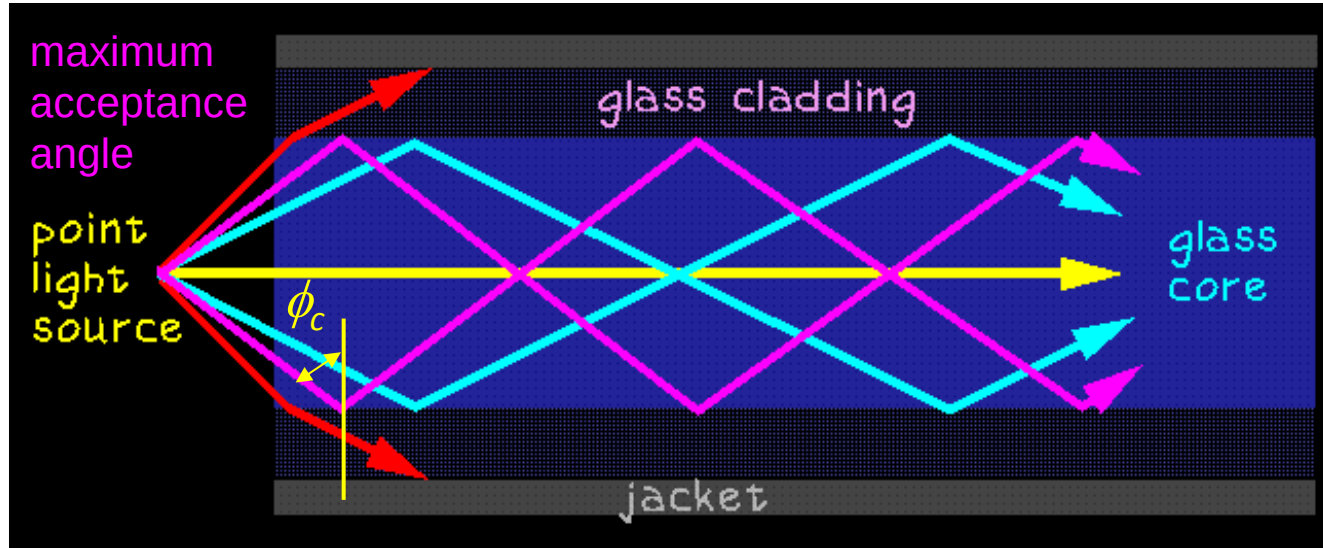
Apply Snell's law to the air-fiber interface: $n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$

With $n_0 = 1$ for air: $\sin \theta_a = (n_1^2 - n_2^2)^{1/2}$

Numerical Aperture (NA): $NA = \sin \theta_a = (n_1^2 - n_2^2)^{1/2} \cong n_1(2\Delta)^{1/2}$

where $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1}$: the relative index difference between the core and the cladding.

Light Transmission in a Multimode Fiber



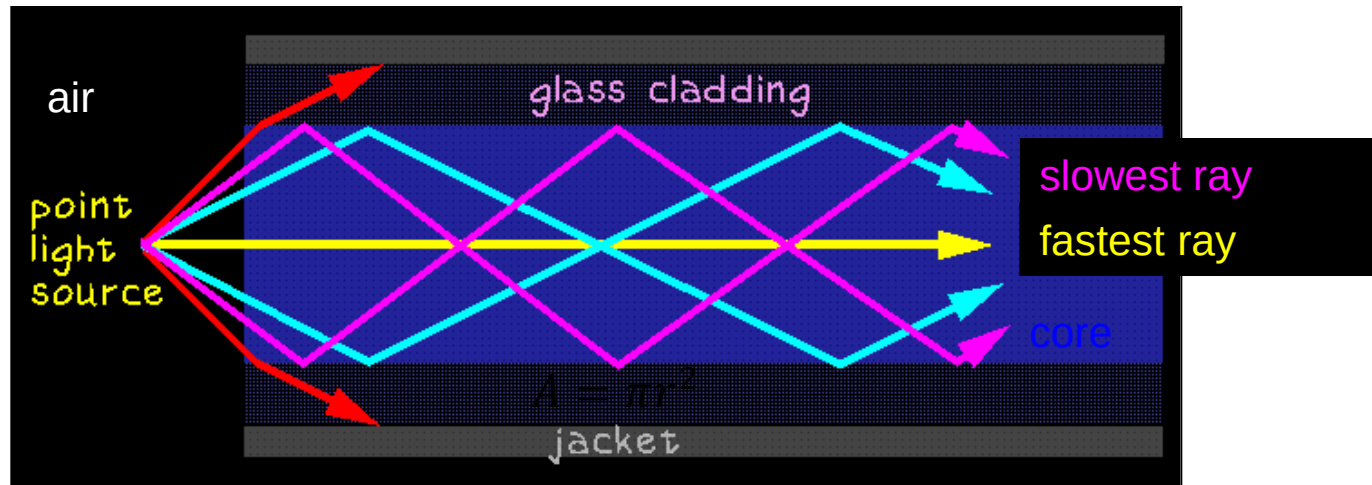
Core/cladding index difference: $\Delta = 1\%$
Critical angle: $\phi_c \sim 82^\circ$
Maximum acceptance angle: $\theta_a \sim 12^\circ$
NA ~ 0.21

Core/cladding index difference: $\Delta = 2\%$
Critical angle: $\phi_c \sim 79^\circ$
Maximum acceptance angle: $\theta_a \sim 17^\circ$
NA ~ 0.29

Only light collected within the maximum acceptance angle can be trapped into the core of the fiber. NA is a useful measure of the light-collecting ability of a multimode fiber.

Light Transmission in a Multimode Fiber

Pulse Broadening by Modal Dispersion



Time delay between the slowest ray and the fastest ray:

$$\delta T = \frac{Ln\Delta}{c}$$

Pulse broadening δT is proportional to Δ .

L : fiber length; n : refractive index of core (~ 1.45); c : speed of light in vacuum

Maximum bit rate: $B_{max} = \frac{1}{2\delta T}$

Example

A 6 km optical link consists of a multimode step-index fiber with a relative refractive index difference of 1% ($n_1 = 1.5$).

$$\delta T = \frac{Ln\Delta}{c} = \frac{6 \times 10^3 \times 1.5 \times 0.01}{3.0 \times 10^8} = 300\text{ns or } 50\text{ns/km}$$

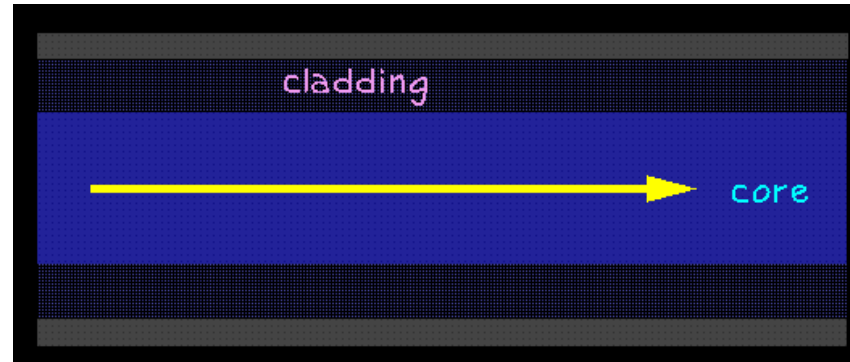
Maximum bit rate can be estimated as

$$B_{max} = \frac{1}{2\delta T} = \frac{1}{2 \times 300 \times 10^{-9}} = 1.7 \text{ Mbit/s}$$

What will be the maximum bit rate if the fiber link is 1 km long?

The maximum bit rate can be increased by two to three orders of magnitude with a **graded-index fiber** whose refractive-index profile in the core is carefully designed to minimize the pulse broadening effect.

Light Transmission in a Single-Mode Fiber



Only the fundamental mode is supported by the fiber, so that pulse broadening caused by modal dispersion is eliminated.

Condition for [single-mode operation](#) (step-index profile)

$$V = \frac{2\pi}{\lambda} a n \sqrt{2\Delta} < 2.405$$

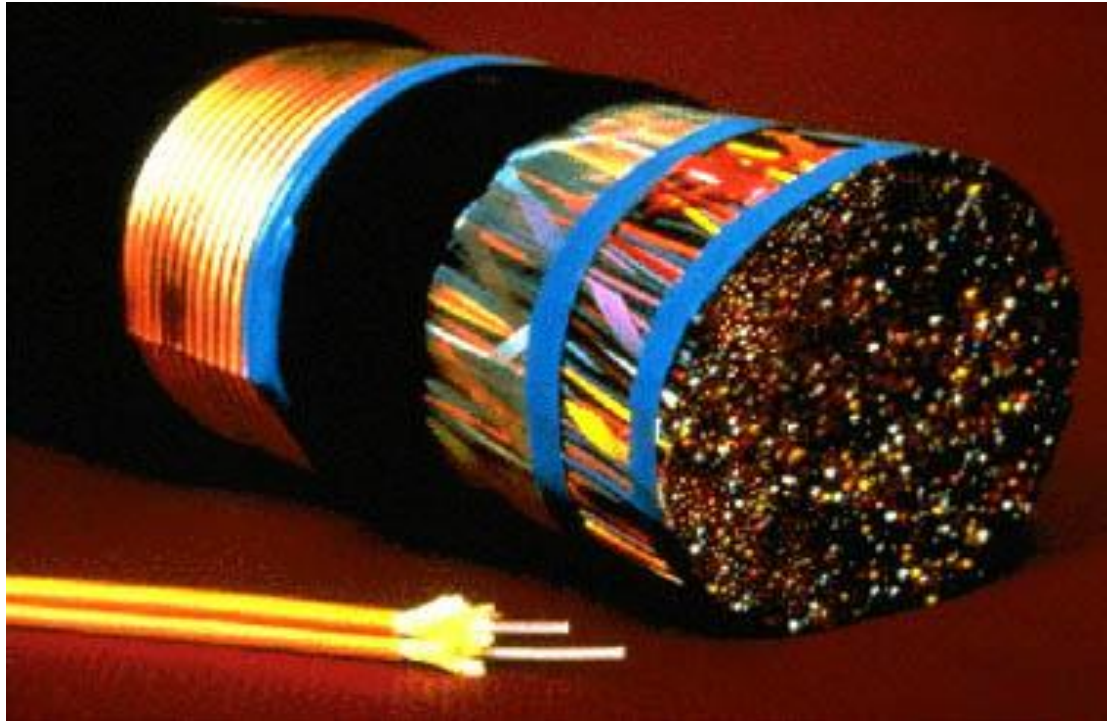
a : core radius; n : refractive index of core (~ 1.45); λ : free-space wavelength

Single-mode operation at the wavelength $1.2 \mu\text{m}$:

For $\Delta = 3 \%$, maximum $2a = 2.6 \mu\text{m}$; For $\Delta = 0.3 \%$, maximum $2a = 8.2 \mu\text{m}$

[A carefully designed single-mode fiber system can provide a bit rate higher than 10 Gb/s \(i.e., support more than 120,000 telephone channels\).](#)

Comparison of Fiber and Copper Cables



<http://www.corningcablesystems.com/web/college/fibertutorial.nsf/introfro?OpenForm>

The fiber cable in the foreground has the same signal-carrying capacity of the copper cable in the background.

Fiber optic cables: How they work (5 min)

https://www.youtube.com/watch?v=0MwMkBET_5I

Wavelength-Division Multiplexing (WDM)

Wavelength-division multiplexing (WDM) is a technology which multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths (i.e., colors) of light.

Multiplexing of the wavelengths in a WDM system can be done in two different ways, depending on how much bandwidth each wavelength is allocated on the optical fiber: Coarse (CWDM) and Dense (DWDM).

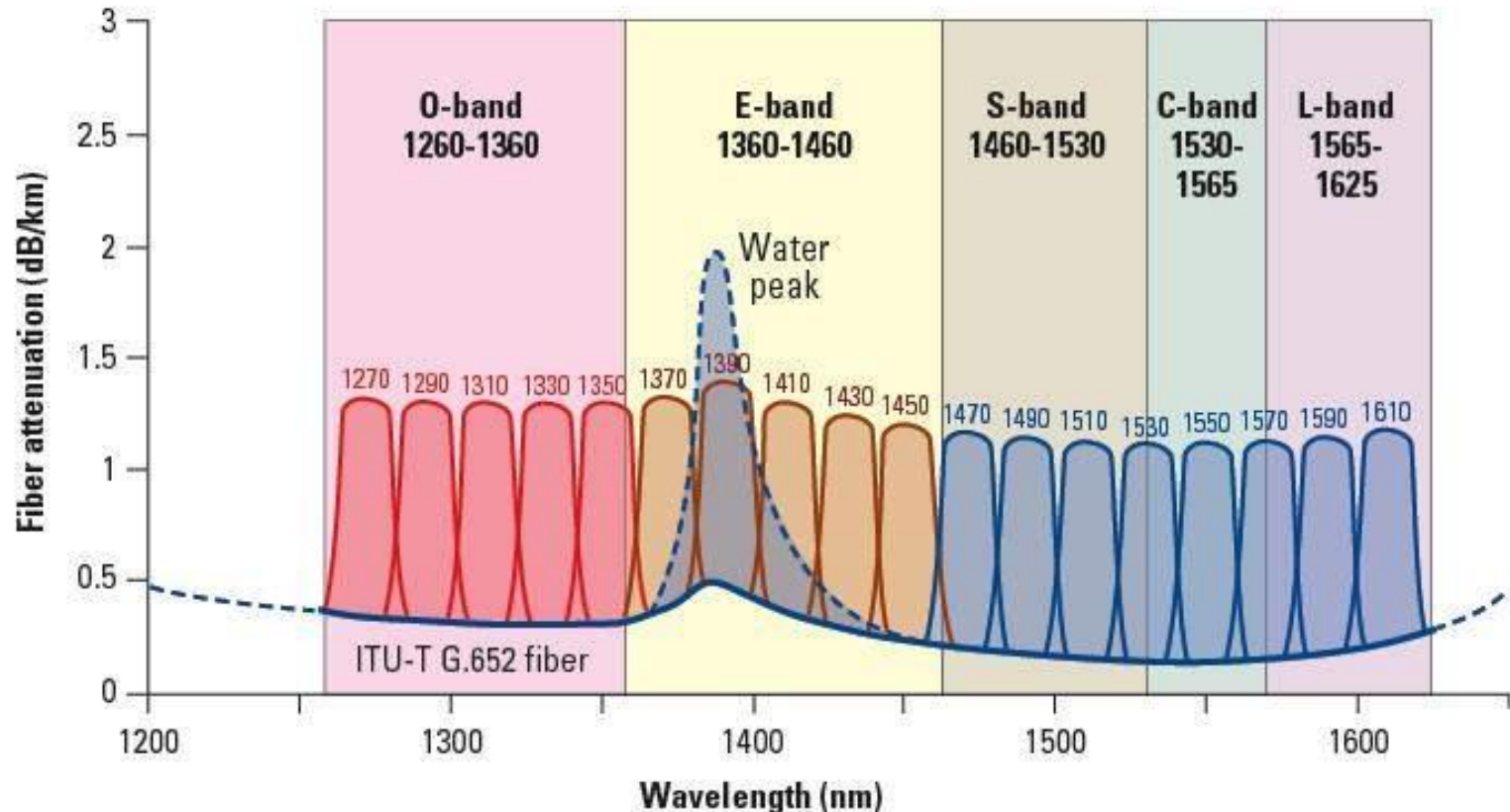
CWDM can provide up to 8 wavelength channels in the 1470 to 1610 nm range and 8 additional channels in the 1270 to 1450 nm range, i.e., a total maximum of 16 CWDM channels.

DWDM uses a smaller transmission window than CWDM but with much denser channel spacing. The DWDM channels are normally located in the 1530 to 1565 nm range (the C-band). An additional set of DWDM channels have been standardized for the 1570 to 1600 nm range (the L-band), making it theoretically possible to more or less double the capacity of a fiber. However, components for the L-band are not as common as for the C-band and there are virtually no pluggable transceivers available for the L-band, making the C-band the most economical alternative for DWDM. 40 channels at 100 GHz (~0.8 nm) spacing or 80 channels with 50 GHz (~0.4 nm) spacing in the C-band are available.

<http://www.transmode.com/en/technologies/wdm-the-transmode-way/wdm-the-transmode-way-html/2-wdm-networking-technologies>

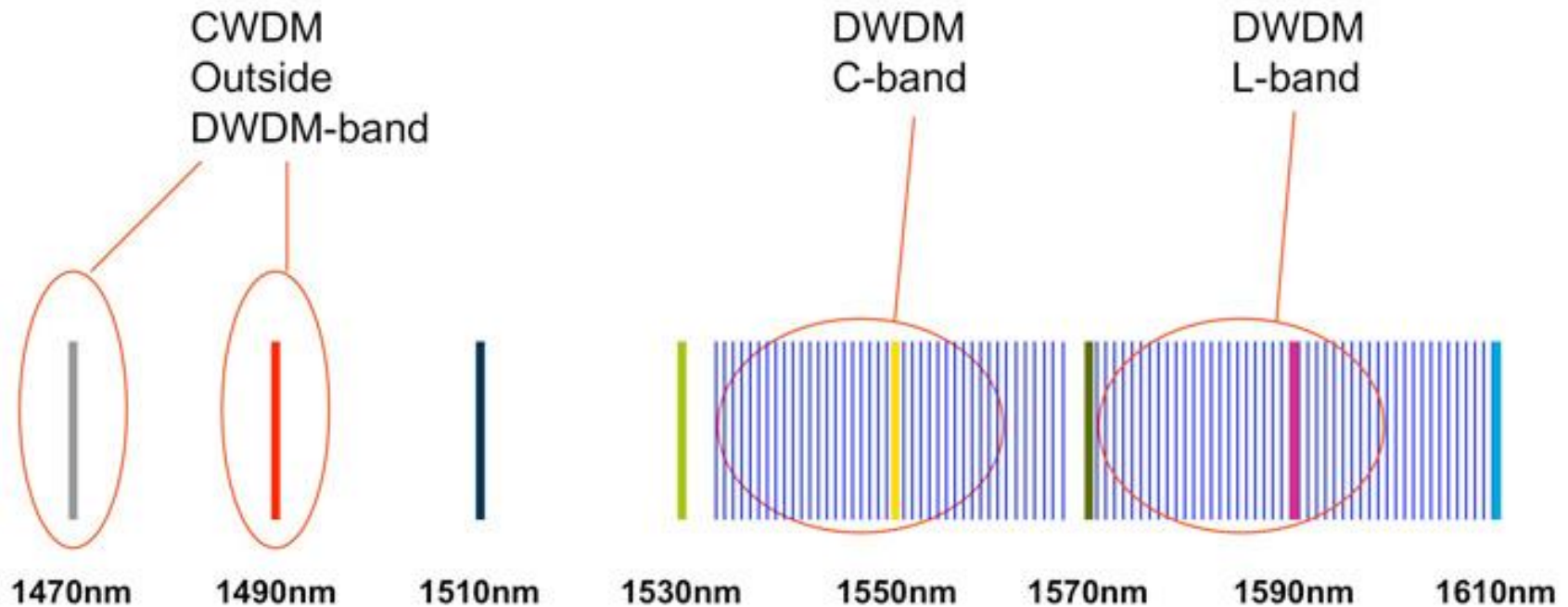
Wavelength-Division Multiplexing (WDM)

CWDM wavelength grid as specified by ITU-T G.694.2



<http://www.cianet.ind.br/pt/produtos/tecnologias/tecnologia-wdm/>

Wavelength-Division Multiplexing (WDM)



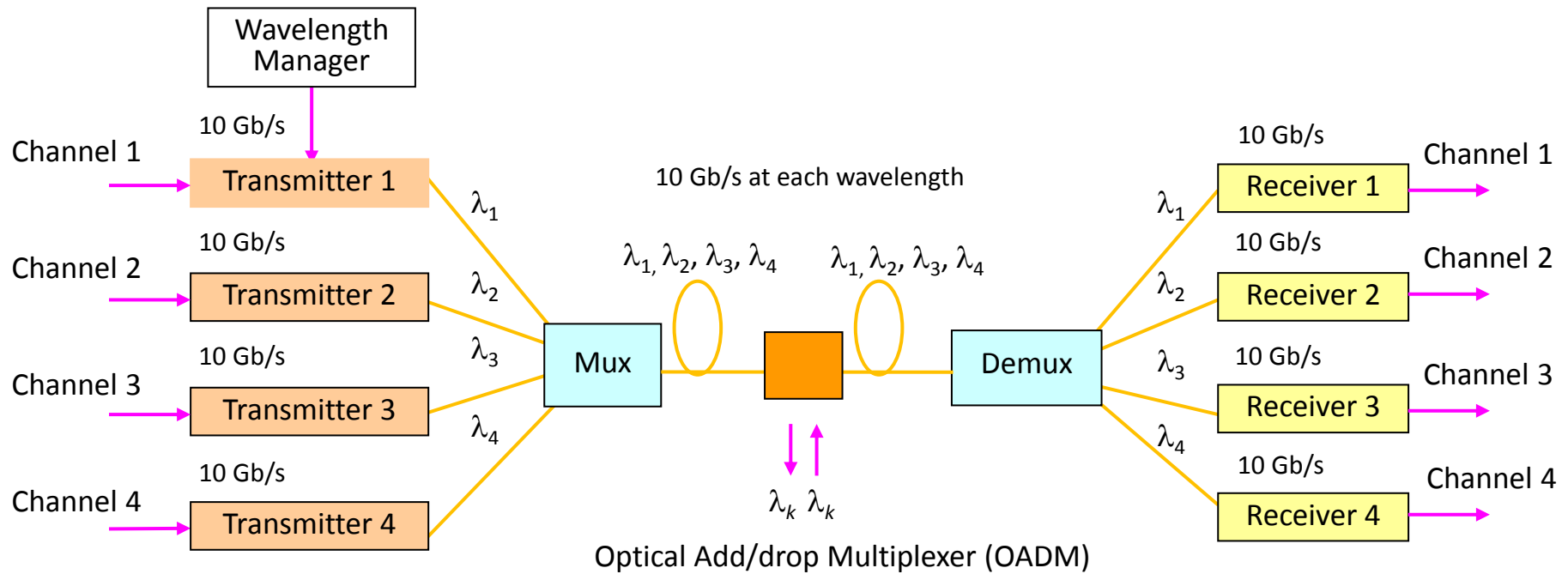
<http://www.transmode.com/en/technologies/wdm-the-transmode-way/wdm-the-transmode-way-html/2-wdm-networking-technologies>

Total DWDM bandwidth for a single-mode fiber over the C+L band:

160 channels x 10 Gb/s = 1600 Gb/s (1.6 Tb/s)

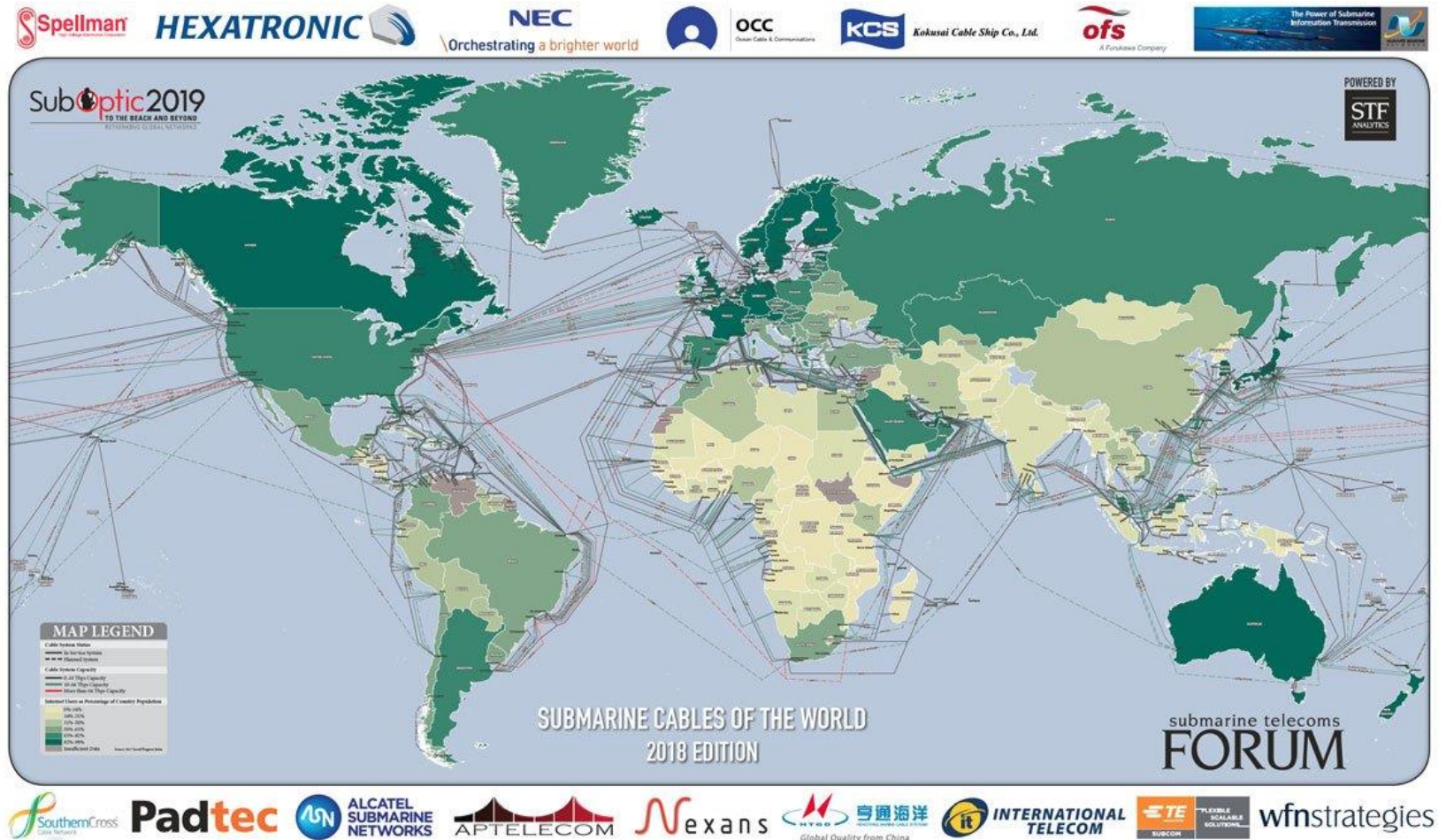
80 channels x 40 Gb/s = 3200 Gb/s (3.2 Tb/s) (all books in a moderate library)

Wavelength-Division Multiplexing (WDM)



For a long transmission distance (~ 100 km), amplification of the WDM channels is required. **Erbium-doped fiber amplifier (EDFA)** can provide optical amplification for all the channels in the C-band.

Optical Communication Systems



https://subtelforum.com/products/submarine-cable-map/?gclid=EAIaIQobChMIstOU_uGd3AIVh5K9Ch2w9gNWEAAYASAAEgJSCfD_BwE

The first fiber submarine system: TAT-8 (12/1988)

US, The UK, France

1.3 μm , 280 Mbit/s · 2 Fiber pairs, 40,000 telephone circuits

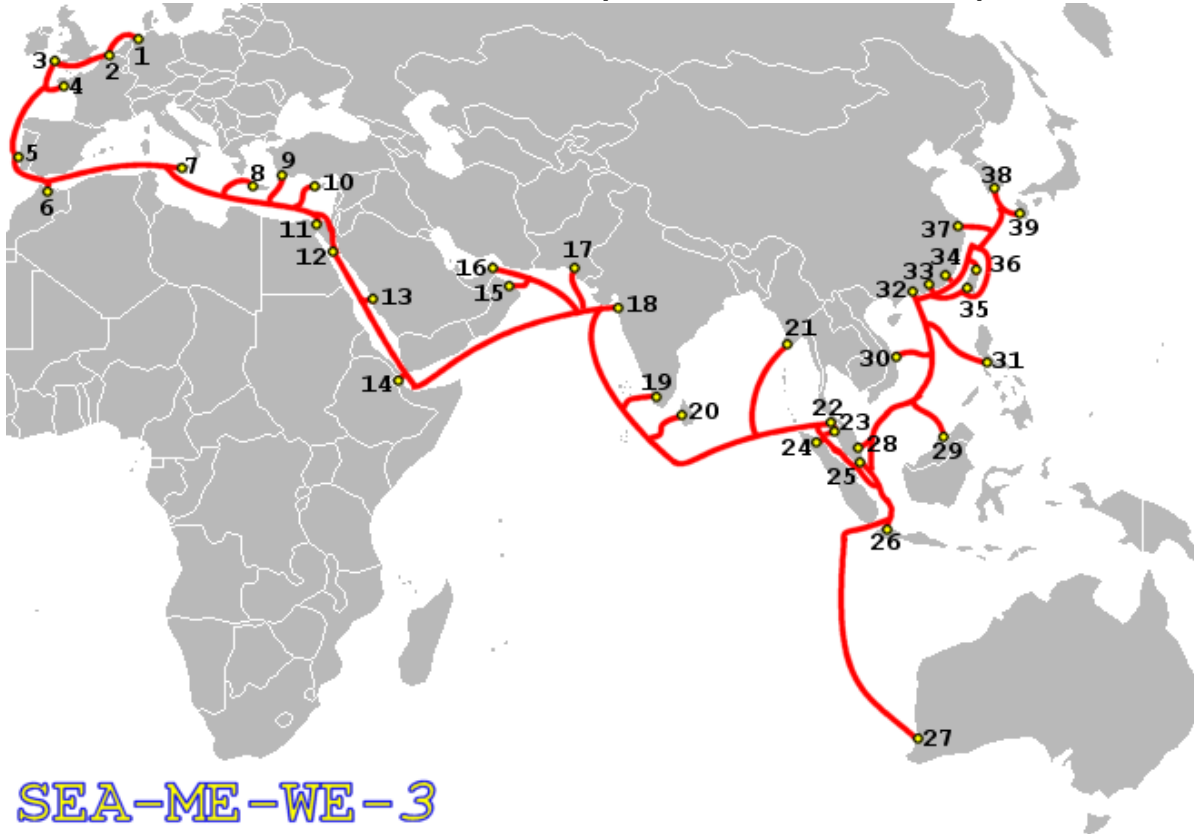
109 Electronic Repeaters

* First submarine coaxial system: TAT-1, 48 channels (1956 – 1978)

SEA-ME-WE-3 (2000)

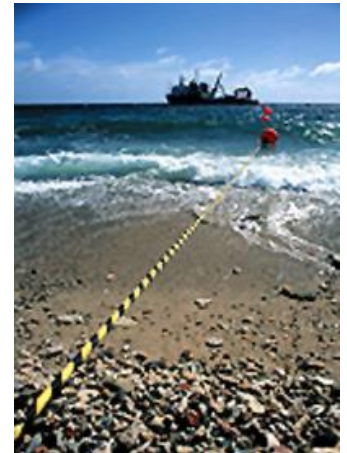
39 Landing points; 39,000 km

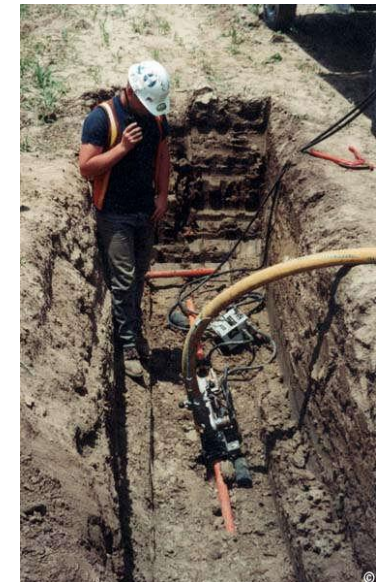
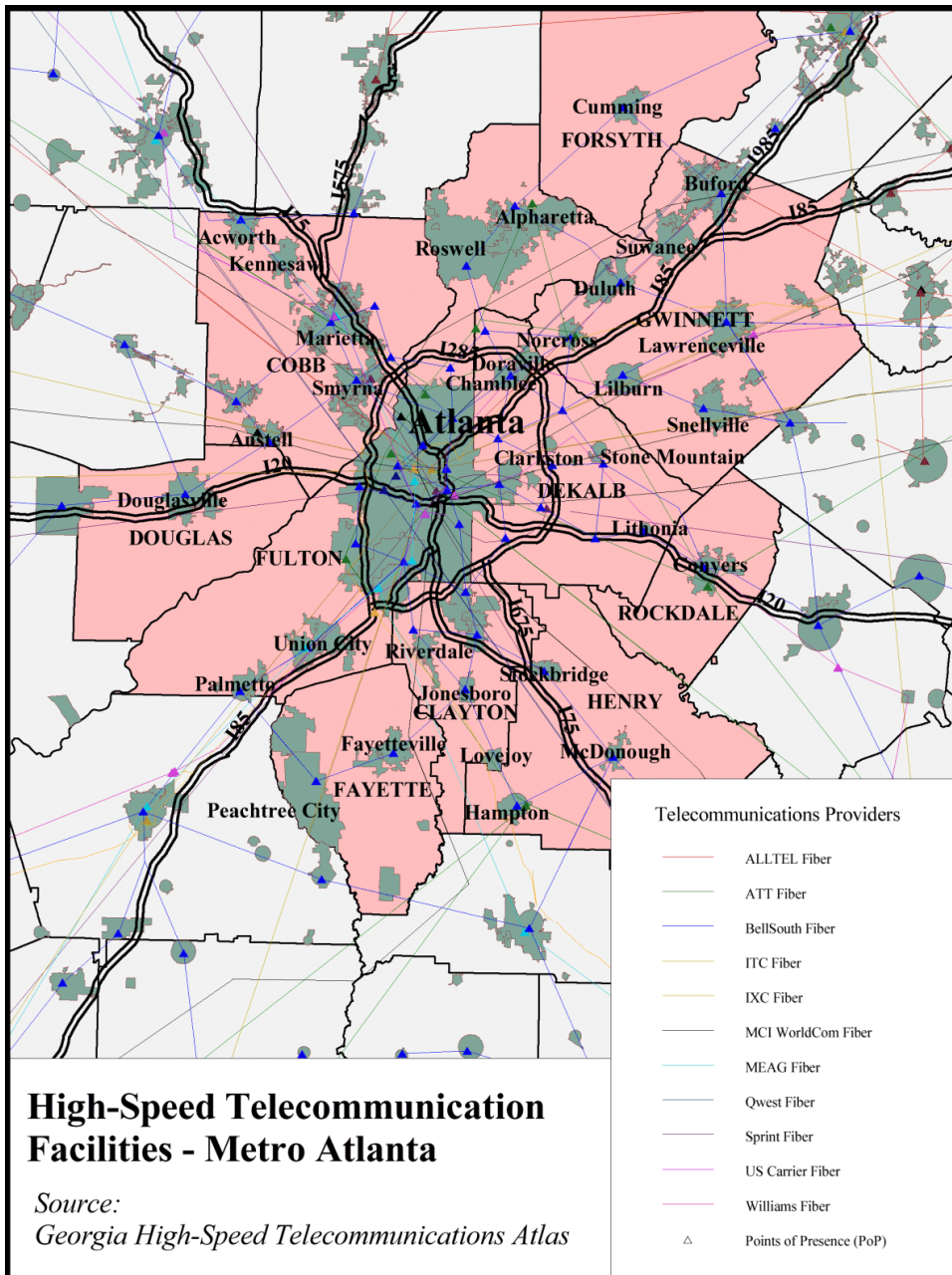
10 Gb/s · 48 WDM · 2 Fiber pairs – 960 Gb/s (after 2007 upgrade)



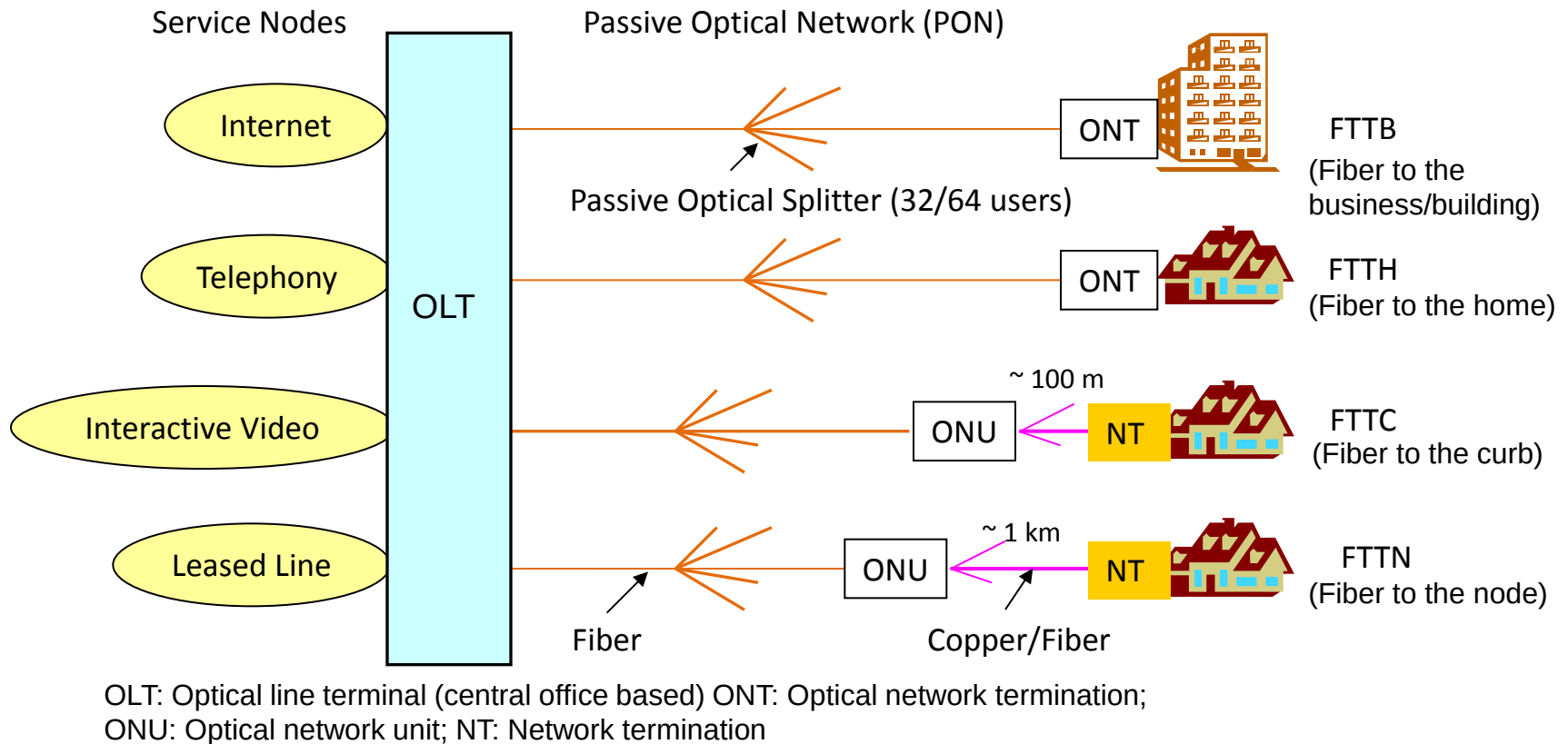
SEA-ME-WE-3

https://en.wikipedia.org/wiki/SEA-ME-WE_3





Local Access Networks

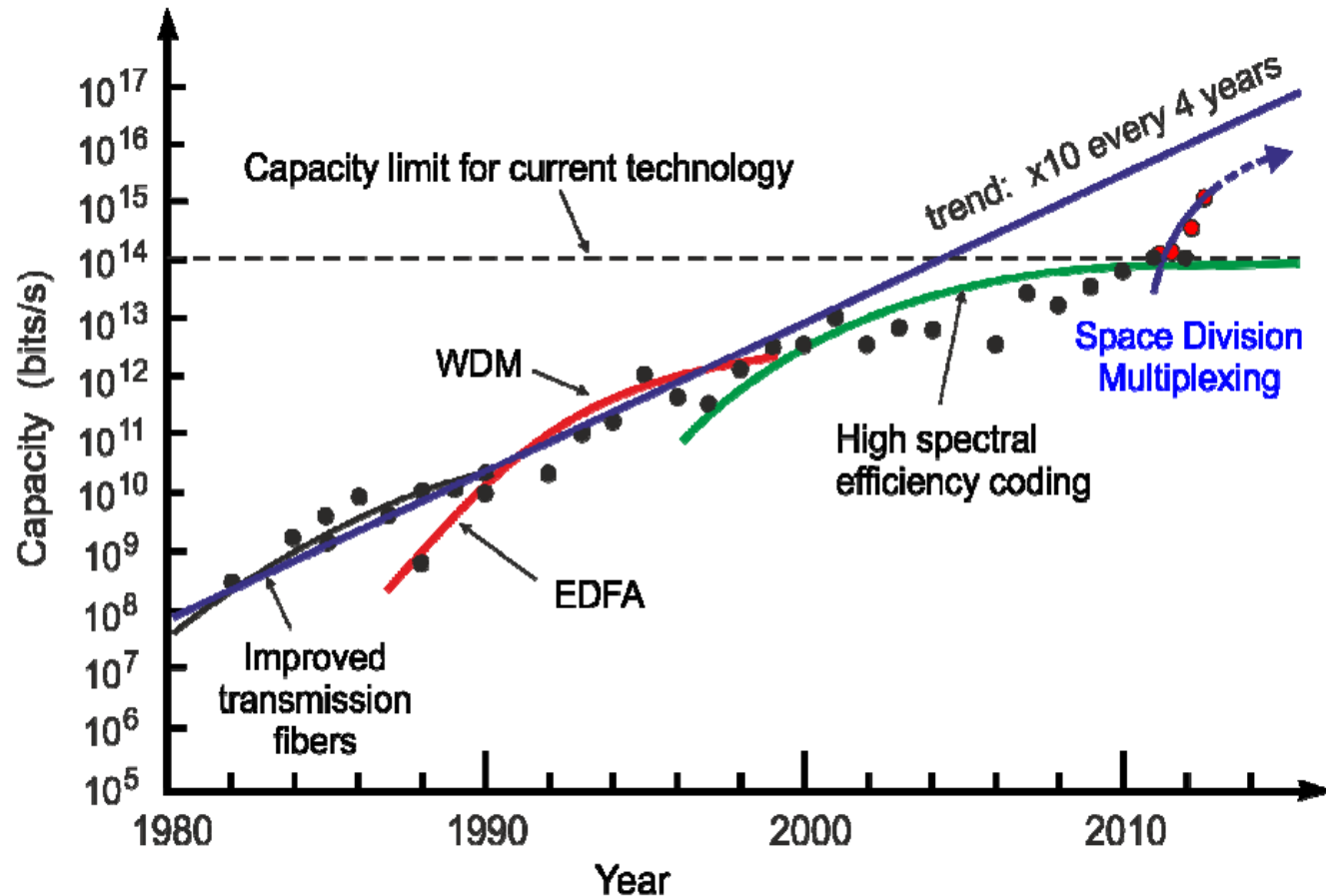


Advanced broadband services (triple play: voice, data, video):

Fast Internet access, electronic commerce, video on demand, digital broadcasting, teleconferencing, telemedicine, e-learning, etc.

Delivery of these services effectively to the last mile of homes and businesses demand a large bandwidth.

Evolution of Optical Fiber Communication



Capacity limit of a single-mode fiber: **~100 Tb/s**

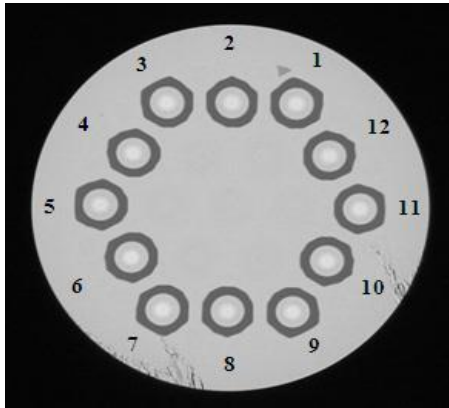
[D. J. Richardson *et al.*, *Nature Photonics* 7 (2013) 354]

Evolution of Optical Fiber Communication

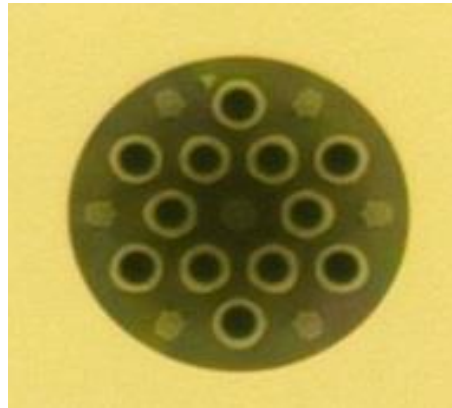
Three “M” technologies:

- Multicore fibers (space-division multiplexing)
- Multimode fibers (mode-division multiplexing)
- Multi-level coding

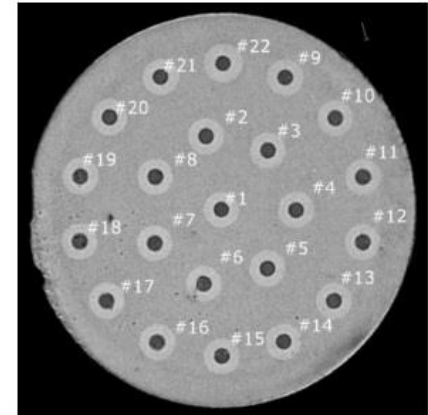
Multicore fibers



2012



2013



2015

Few-mode fibers

A fibre supports a small number of modes. A carefully designed few-mode fibre with minimized differential group delays among the modes (intermodal dispersion) can be used for mode-division-multiplexing applications.

Exercise

1. A silica multimode optical fiber has a core refractive index of 1.465 and a cladding refractive index of 1.444. Determine (a) the critical angle at the core-cladding interface; (b) the numerical aperture (NA) of the fiber; (c) maximum acceptance angle in air for the fiber.
2. A typical relative refractive index difference for a multimode optical fiber designed for short distance transmission is 3%. Estimate the NA and the critical angle at the core-cladding interface with the fiber, assuming the core index is 1.470.
3. When the mean optical power launched into a 6 km length of fiber is 1.5 mW, the mean optical power at the fiber output is 47 μ W. Determine (a) the overall signal attenuation of loss in dB through the fiber assuming there are no splices or connectors; (b) the signal attenuation per kilometer for the fiber; (c) the overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB; (d) the input/output power ratio in (c).

Exercise (Continue)

4. A 8 km optical link consists of a multimode step-index fiber with a core refractive index of 1.475 and a relative refractive index difference of 1.5%. Estimate the delay difference between the slowest and fastest rays at the fiber output (i.e., the pulse broadening δT) and the maximum bit rate that the fiber link can support. What will be the maximum bit rate of the fiber, if it is 1 km long?
5. Determine the cutoff wavelength for a step-index fiber to exhibit single-mode operation when the core refractive index and radius are 1.46 and 4.0 μm , respectively, with the relative index difference being 0.30%.
6. A single-mode step-index fiber designed for operation at a wavelength of 1.55 μm has core and cladding refractive indices of 1.457 and 1.450, respectively. When the core diameter is 7.0 μm , confirm that the fiber will permit single-mode transmission and estimate the range of wavelengths for single-mode operation of the fiber.