S-72.3320 Advanced Digital Communication (4 cr)

Fiber-optic Communications

Targets today

- To understand basic features of fiber-optic communications
- To understand basic operation principles of optical cables and determination of performance limits of optical communications
  - based on fiber physics
  - link bandwidth and bit rate
- To understand in qualitative level how LEDs and lasers work
- To understand optical link evolution and basics of optical amplifiers

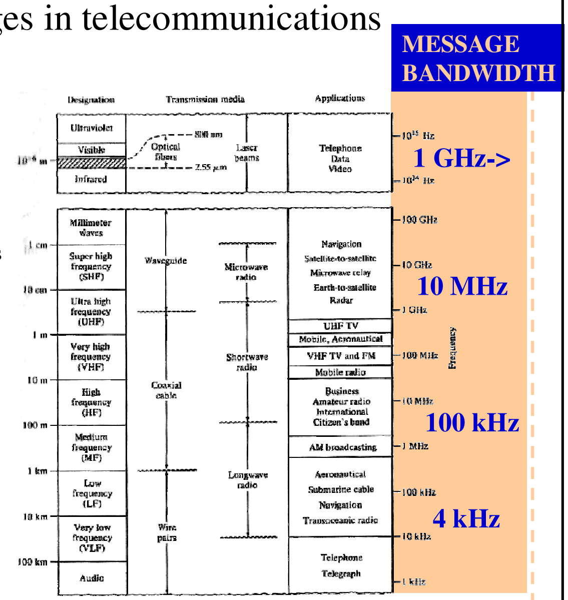
Timo O. Korhonen, HUT Communication Laboratory

Fiber-optic Communications

- Frequency ranges in telecommunications
- Advantages of optical systems
- Optical fibers - basics
  - single-mode fibers
  - multi-mode fibers
- Modules of a fiber optic link
- Optical repeaters - EDFA
- Dispersion in fibers
  - inter-modal and intra-modal dispersion
- Fiber bandwidth and bit rate
- Optical sources: LEDs and lasers
- Optical sinks: PIN and APD photodiodes
- Basics of optical link design

Frequency ranges in telecommunications

- Increase of telecommunications capacity and rates requires higher carrier frequencies
- Optical systems
  - started with links, nowadays also in networks
  - can use very high bandwidths
  - repeater spacing up to thousands of km
  - apply predominantly low-loss silica-fibers
- Optical communications is especially applicable in
  - MPLS (RFC 3031)
  - FDDI (ANSI X3T9.5)
  - Gb-Ethernet (1000BASE-T)
  - ATM, (specifications, see ATM Forum homepage)



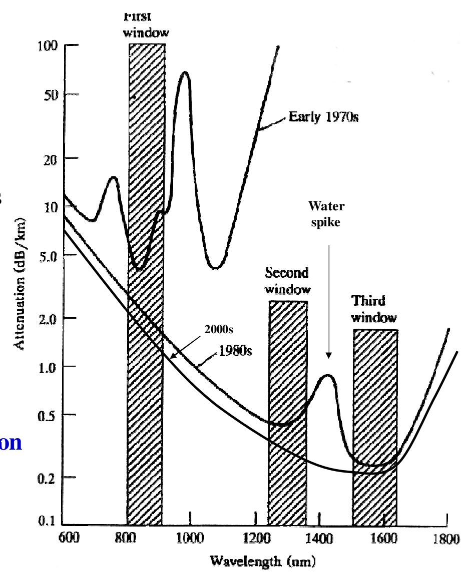
Advantages of optical systems

- Enormous **capacity**: 1.3 µm ... 1.55 µm allocates bandwidth of 37 THz!!
- Low transmission **loss**
  - Optical fiber loss can be as low as 0.2 dB/km. Compare to loss of coaxial cables: 10 … 300 dB/km !
- Cables and equipment have **small size and weight**
  - A large number of fibers fit easily into an optical cable
  - Applications in special environments as in aircrafts, satellites, ships
- **Immunity** to interference
  - Nuclear power plants, hospitals, EMP (Electromagnetic pulse) resistive systems (installations for defense)
- Electrical **isolation**
  - electrical hazardous environments
  - negligible crosstalk
- Signal **security**
  - banking, computer networks, military systems
- Silica fibers have **abundant raw material**

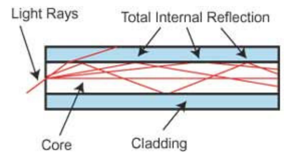
Corning's standard submarine cables can have up to 144 fibers in a single cable housing

Optical fibers - attenuation

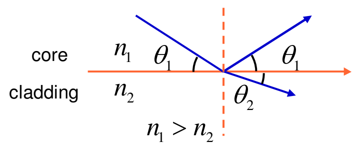
- Traditionally two windows available:
  - 1.3 µm and 1.55 µm
- The lower window is used with Si and GaAlAs and the upper window with InGaAsP compounds
- Nowadays these attenuation windows no longer separate (water-spike attenuation region can be removed)
- There are **single**- and **monomode** fibers that may have step or graded refraction index profile
- Propagation in optical fibers is influenced by **attenuation**, **scattering**, **absorption**, and **dispersion**
- In addition there are **non-linear** effects that are important in **WDM-transmission**



Characterizing optical fibers



- Optical fiber consist of (a) core
  (b) cladding
  (c) mechanical protection layer
- Refraction index of the core n_1 is slightly larger causing **total internal refraction** at the interface of the core and cladding



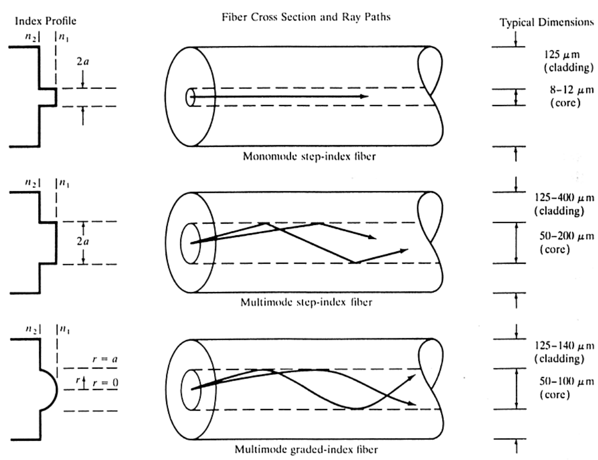
$$n_1 \approx 1.48 \quad \Delta \approx 0.01 \quad n_2 = n_1(1-\Delta)$$

$$n_1 \cos\theta_1 = n_2 \cos\theta_2$$

$$n_1 \sin(\pi/2-\theta_1) = n_2 \sin(\pi/2-\theta_2)$$

- Fibers can be divided into singe-mode and multimode fibers
  - Step index
  - Graded index
  - WDM fibers (single-mode only)
- WDM-fibers designed to cope with fiber non-linearities (for instance Four Wave Mixing)

Mechanical structure of single-mode and multimode step/graded index fibers



Fiber modes

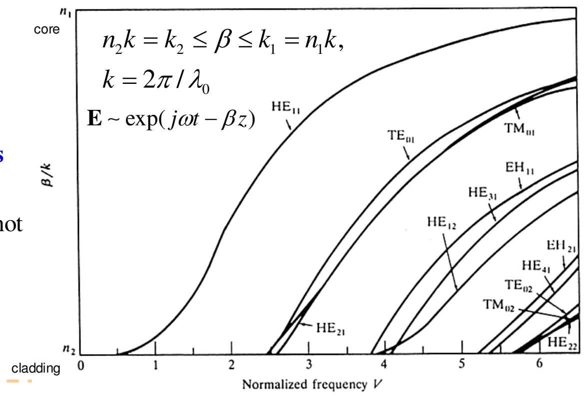
- Electromagnetic field propagating in fiber can be described by Maxwell's equations whose solution yields number of modes *M*.
  For a step index profile

$$M \approx V^2/2, \text{ where } V^2 \approx \left(\frac{2\pi a}{\lambda}\right)^2 \left(n_1^2 - n_2^2\right)$$

  where *a* is the core radius and *V* is the mode parameter (or normalized frequency of the fiber)
- Depending on fiber parameters, number of different propagating modes appear
- **For single mode fibers**

$$V \leq 2.405$$

- Single mode fibers do not have mode dispersion
  (see the supplementary 'Mode Theory' for further details)



Fiber modes (cont.)

2.4 MODE THEORY FOR CIRCULAR WAVEGUIDES 43

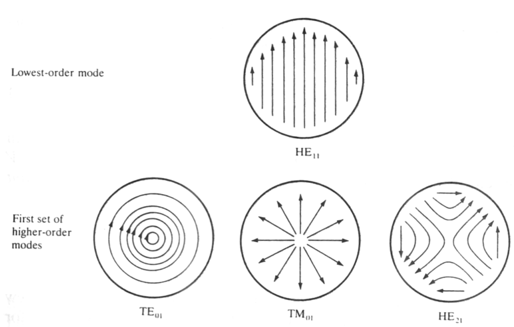
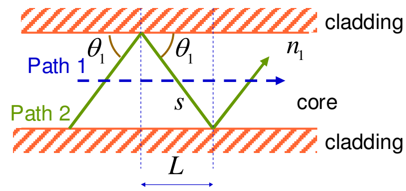


FIGURE 2-17
Cross-sectional views of the transverse electric field vectors for the four lowest-order modes in a step-index fiber.

Gerd Keiser: Optical Fiber Communications, 2th ed

Inter-modal (mode) dispersion

- Multimode fibers exhibit modal dispersion that is caused by different propagation modes taking different paths:



$$\delta_{mod} = T_{max} - T_{min}$$

$$\begin{cases} v = s/t \\ v = c/n \end{cases}$$

$$\Delta = (n_1 - n_2)/n_1 \qquad n_2 = n_1(1-\Delta) \quad n_1 \cos\theta_1 = n_2 \cos\theta_2$$

$$n_1 \cos\theta_1 = n_2 \cdot \cos(0) \qquad \cos\theta_1 = n_2/n_1 = 1-\Delta = L/s$$

$$s = L/\cos\theta_1 = L/(1-\Delta)$$

$$T_{max} = s/v = L/\left[(1-\Delta)c/n_1\right] \qquad T_{min} = \frac{L}{c/n_1}$$

$$\delta_{mod} = T_{max} - T_{min} = Ln_1/\left[c(1-\Delta)\right] - Ln_1/c$$

$$\delta_{mod} = \frac{Ln_1}{c}\left(\frac{\Delta}{1-\Delta}\right) \approx \frac{Ln_1}{c}\Delta$$

Chromatic dispersion

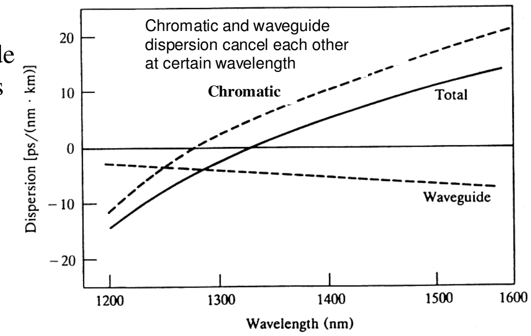
- Chromatic dispersion (or material dispersion) is produced when different frequencies of light propagate in fiber with different velocities
- Therefore chromatic dispersion is larger the wider source bandwidth is. Thus it is largest for LEDs (Light Emitting Diode) and smallest for LASERs (Light Amplification by Stimulated Emission of Radiation) diodes
- LED BW is about 5% of λ_0, Laser BW about 0.1 % or below of λ_0
- Optical fibers have dispersion minimum at 1.3 μm but their attenuation minimum is at 1.55 μm. This gave motivation to develop dispersion shifted fibers .

Example: GaAlAs LED is used at λ_0=1 μm. This source has spectral width of 40 nm and its material dispersion is D_{mat}(1 μm)=40 ps/(nm x km). How much is its pulse spreading in 25 km distance?

$$\sigma_{mat} = 40\,\text{nm} \cdot 40 \frac{\text{ps}}{\text{nm} \cdot \text{km}} \cdot 25\,\text{km} = 40\,\text{ns}$$

Chromatic and waveguide dispersion

- In addition to chromatic dispersion, there exists also waveguide dispersion that is significant for single mode fibers in longer wavelengths
- Chromatic and waveguide dispersion are denoted as intra- modal dispersion and their effects cancel each other at a certain wavelength
- This cancellation is used in dispersion shifted fibers

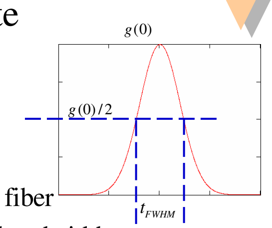


- Total dispersion is determined as the geometric sum of intra-modal and inter-modal (or mode) dispersion with the net pulse spreading:

$$\sigma_{tot}^2 = \sigma_{\text{intermod}}^2 + \sigma_{\text{intramod}}^2 \qquad \text{(uncorrelated random variables)}$$

Dispersion due to different mode velocities → (intermod); waveguide+chromatic dispersion → (intramod)

Determining link bit rate



- Link bit rate limited by
  - **linewidth** (bandwidth) of the optical source
  - **rise time** of the optical source and detector
  - **dispersion** (linear/nonlinear) properties of the fiber
- All above cause pulse spreading that reduces link bandwidth
- Assume optical power emerging from the fiber has the Gaussian shape

$$g(t) = \exp\left(-t^2/2\sigma^2\right)/\left(\sqrt{2\pi}\sigma\right) \Rightarrow \quad G(\omega) = \exp\left(-\omega^2\sigma^2/2\right)/\sqrt{2\pi}$$

- From the time-domain expression the time required for pulse to reach its half-maximum, e.g the time to have $g(t_h)=g(0)/2$ is

$$t_h = (2\ln 2)^{1/2}\sigma = t_{FWHM}/2$$

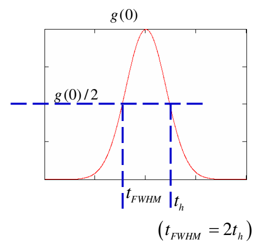
where t_{FWHM} is the Full-Width-Half-Maximum(FWHM) pulse width
- Relationship between fiber risetime and bandwidth is (next slide)

$$f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}}$$

Relationship between 3 dB bandwidth and rise time

- Gaussian pulse in time and frequency domain

$$\begin{cases} g(t) = \exp\left(-t^2/2\sigma^2\right)/\left(\sqrt{2\pi}\sigma\right) \\ G(\omega) = \exp\left(-\omega^2\sigma^2/2\right)/\sqrt{2\pi} \end{cases} \Rightarrow$$



- Solve rise time and 3 dB bandwidth from both

$$\begin{cases} g(t_h) - \dfrac{g(0)}{2} = 0 \Rightarrow t_h = f(\sigma) \\ G(f_{3\mathrm{dB}}) - \dfrac{G(0)}{2} = 0 \Rightarrow f_{3\mathrm{dB}} = f(\sigma) \end{cases}$$

$$\Rightarrow f_{3\mathrm{dB}} = f(t_h) = \frac{\ln 2}{\pi t_h} \approx \frac{0.44}{t_{FWHM}}$$

- Note that t_h is the 0-to-50% rise time. In electrical domain one usually applies 10-to-90% rise time, denoted by t_r.

Calculus by using Mathcad in lecture supplementary

Total system rise-time

- Total system rise-time can be expressed* as

$$t_{sys} = \left[t_{tx}^2 + D_{\mathrm{mat}}^2 \sigma_\lambda^2 L^2 + \left(\frac{440 L^q}{B_0}\right)^2 + \left(\frac{350}{B_{rx}}\right)^2 \right]^{1/2}$$

transmitter rise-time, intra-modal dispersion, inter-modal dispersion, receiver rise-time

where L is the fiber length [km] and q is the exponent characterizing bandwidth. Generally, fiber bandwidth is often expressed by

$$B_M(L) = \frac{B_0^{'}}{L^q}$$

- Bandwidths are expressed here in [MHz] and wavelengths in [nm]
- Here the receiver rise time (*10-to-90-% BW*) is derived based 1. order lowpass filter amplitude from $g_{LP}(t)$=0.1 to $g_{LP}(t)$= 0.9 where

$$g_{LP}(t) = \left[1 - \exp\left(-2\pi B_{rx} t\right)\right] u(t)$$

* *details in lecture supplementary*

Example

- Calculate the total rise time for a system using LED and a driver causing transmitter rise time of 15 ns. Assume that the led bandwidth is 40 nm. The receiver has 25 MHz bandwidth. The fiber has $400\,\text{MHz}\cdot\text{km}$ bandwidth distance product with q=0.7. Therefore

$$t_{sys} = \left[t_{tx}^2 + D_{\text{mat}}^2 \sigma_\lambda^2 L^2 + \left(\frac{440 L^q}{B_0} \right)^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

$$t_{sys} = \left[(15\,\text{ns})^2 + (21\,\text{ns})^2 + (3.9\,\text{ns})^2 + (14\,\text{ns})^2 \right]^{1/2}$$

$$t_{sys} = 30\,\text{ns}\ (=\sigma_{\text{tot}})$$

- Note that this means that the respective electrical signal bandwidth and binary, sinc-pulse signaling rate are

$$B \approx 350/\sigma_{tot}[ns] \approx 11.7\ \text{MHz} \Rightarrow r = 2B = 23.4\,\text{Mb/s}$$

- In practice, for instance binary raised-cos-signaling yields bits rates that are half of this value. (Increasing number of signal levels M increases data rate by the factor of $\log_2(M)$ but decreases reception sensitivity, next slide)

Example: Practical error rate depends on received signal SNR (Pulse-amplitude modulation)

Table 11.2-1 M-ary signaling with $r = 3$ kilobaud and $(S/N)_R = 400$

M	r_b(kbps)	$A/2\sigma$	P_{be}
2	3	20.0	3×10^{-89}
4	6	8.9	1×10^{-19}
8	9	4.4	4×10^{-6}
16	12	2.2	7×10^{-3}
32	15	1.1	6×10^{-2}

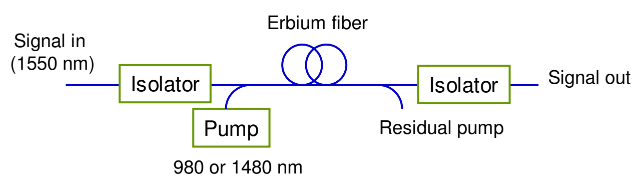
A: Amplitude difference between signaling levels

Ref: A.B.Carlson: Communication Systems, 3rd ed

Optical amplifiers

- Direct amplification of photons (no conversion to electrical signals required)
- Major types:
  - Erbium-doped fiber amplifier at 1.55 μm (EDFA and EDFFA)
  - Raman-amplifier (have gain over the entire rage of optical fibers)
  - Praseodymium-doped fiber amplifier at 1.3 μm (PDFA)
  - semiconductor optical amplifier - switches and wavelength converters (SOA)
- Optical amplifiers versus opto-electrical repeaters:
  - much larger bandwidth and gain
  - easy usage with wavelength division multiplexing (WDM)
  - easy upgrading
  - insensitivity to bit rate and signal formats
- All OAs based on stimulated emission of radiation - as lasers (in contrast to spontaneous emission)
- Stimulated emission yields coherent radiation - emitted photons are perfect clones

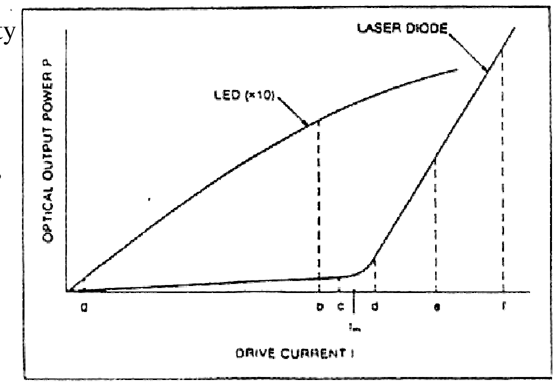
Erbium-doped fiber amplifier (EDFA)



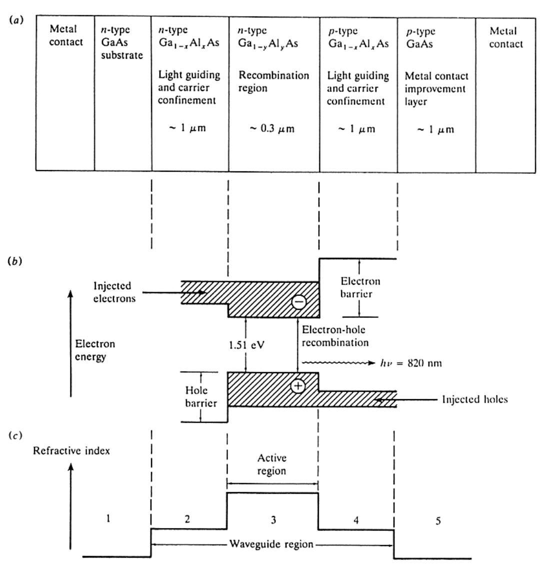
- Amplification (stimulated emission) happens in fiber
- Isolators and couplers prevent resonance in fiber (prevents device to become a laser)
- Popularity due to
  - availability of compact high-power pump lasers
  - all-fiber device: polarization independent
  - amplifies all WDM signals simultaneously

LEDs and LASER-diodes

- Light Emitting Diode (LED) is a simple PN-structure where recombining electron-hole pairs convert current to light
- In fiber-optic communications light source should meet the following requirements:
  - Physical compatibility with fiber
  - Sufficient power output
  - Capability of various types of modulation
  - Fast rise-time
  - High efficiency
  - Long life-time
  - Reasonably low cost

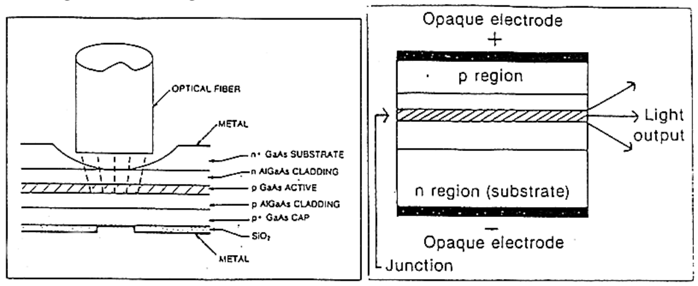


Modern GaAlAs light emitter



Light generating structures

- In LEDs light is generated by spontaneous emission
- In LDs light is generated by stimulated emission
- Efficient LD and LED structures
  - guide the light in recombination area
  - guide the electrons and holes in recombination area
  - guide the generated light out of the structure



a) Surface-emitting LED (SLED)

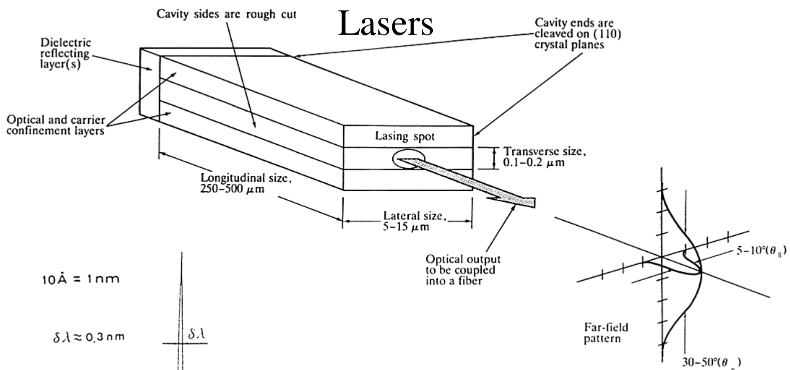
b) Side view of an Edge-emitting LED [24].

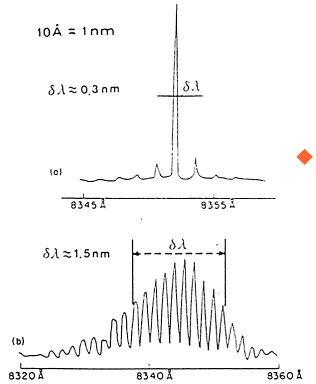
LED types

- Surface emitting LEDs: (SLED) $\delta\lambda \approx 100$ nm ($\delta\lambda =$ FWHM)
  - light collected from the other surface, other attached to a heat sink
  - **no waveguiding**
  - **light coupling** to multimode fibers easy
- Edge emitting LEDs: (ELED) $\delta\lambda = 60-80$ nm
  - like stripe geometry lasers but **no optical feedback**
  - easy coupling into multimode and single mode fibers
- Superluminescent LEDs: (SLD) $\delta\lambda = 30-40$ nm
  - spectra formed *partially* by **stimulated emission**
  - higher optical output than with ELEDs or SLEDs
- For modulation ELEDs provide the best linearity but SLDs provide the highest light output

$\delta\lambda =$ FWHM width

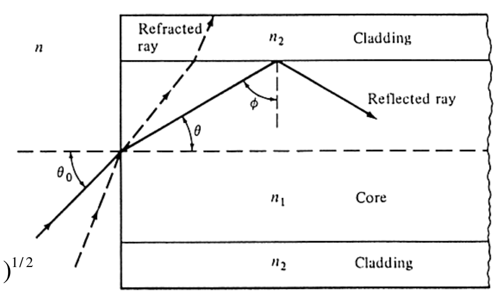
Lasers





- Lasing effect means that stimulated emission is the major form of producing light in the structure. This requires
  - intense charge density
  - direct band-gap material->enough light produced
  - stimulated emission

Connecting optical power



- Numerical aperture (NA):

$$n_2 = n_1(1-\Delta)$$

$$n_1 \cos\theta_1 = n_2 \cos\theta_2$$

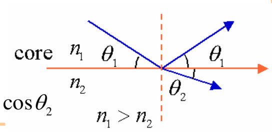
- Maximum (critical) angle supporting internal reflection

$$\Rightarrow \sin\phi_C = n_2 / n_1$$

$$n \sin\theta_{0,\min} = n_1 \sin\theta_C = (n_1^2 - n_2^2)^{1/2}$$

$$\equiv \mathrm{NA} \approx n_1\sqrt{2\Delta}$$

- Connection efficiency is defined by $\eta = P_{fibre} / P_{source}$
- Factors of light coupling efficiency: fiber refraction index profile and core radius, source intensity, radiation pattern, how precisely fiber is aligned to the source, fiber surface quality

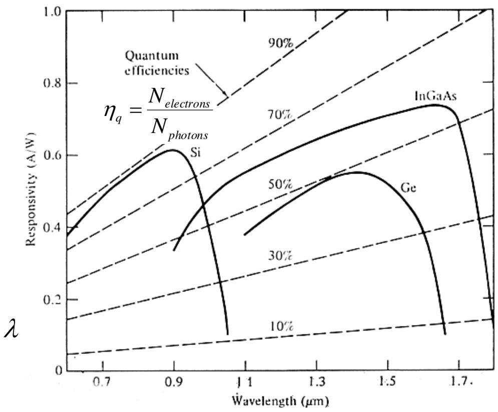


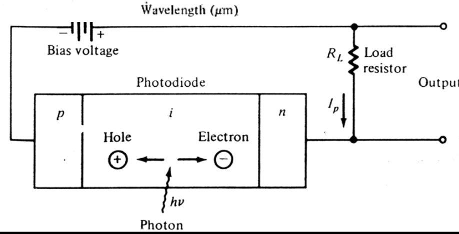
$$n_1 \cos\theta_1 = n_2 \cos\theta_2$$

$n_1 > n_2$

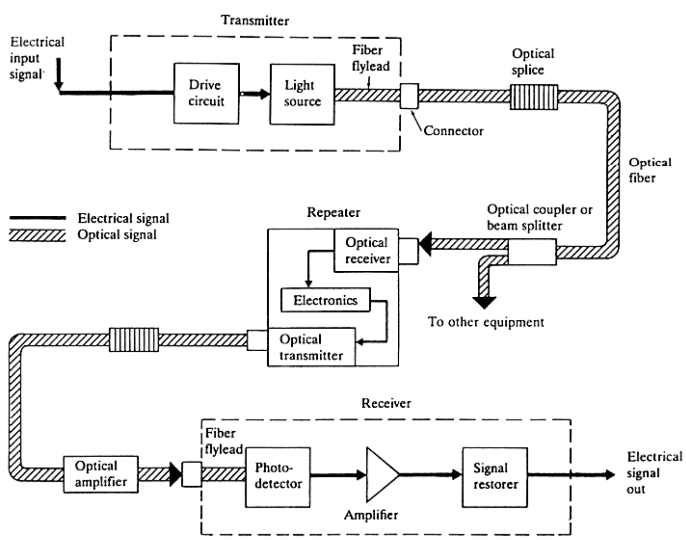
Optical photodetectors (PDs)

- PDs convert photons to electrons
- Two photodiode types
  - PIN
  - APD
- For a photodiode it is required that it is
  - sensitive at the used λ
  - small noise
  - long life span
  - small rise-time (large BW, small capacitance)
  - low temperature sensitivity
  - quality/price ratio

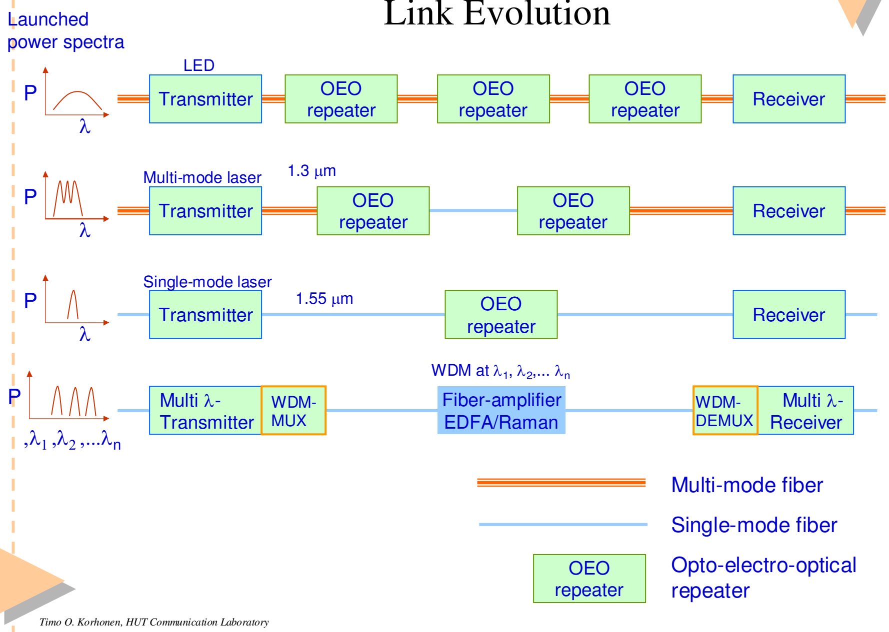




OEO-based optical link of ‘80s

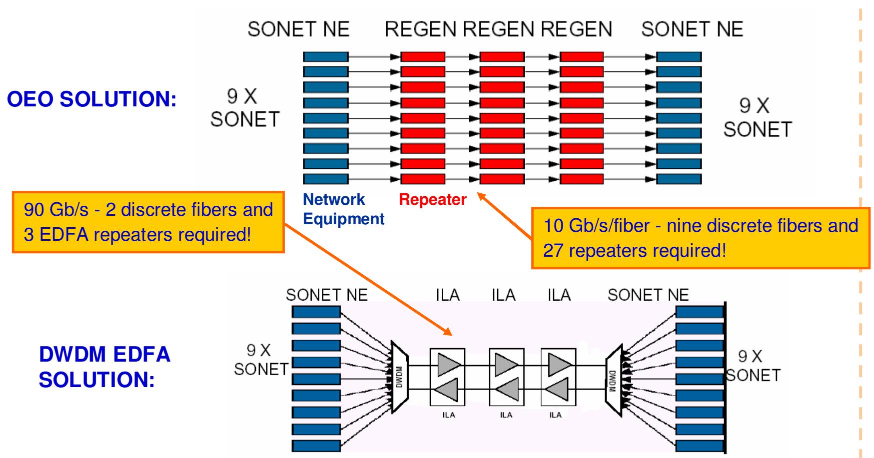


Link Evolution



Timo O. Korhonen, HUT Communication Laboratory

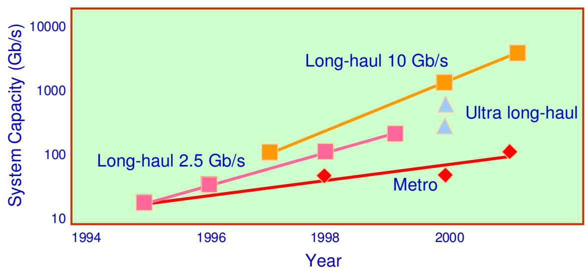
DWDM - technology: Example in SONET Networking Between Exchanges



- **EDFA:** Erbium Doped Fiber Amplifier
- **DWDM:** Dense Wavelength Division Multiplexing
- **SONET**: Synchronous Optical Network is a networking hierarchy analogous to **SDH** Synchronous Digital Hierarchy as applied in PSTN (OC-192 ~9.95 Gb/s [OC-1~51.8 Mb/s])

Tin

Evolution of WDM System Capacity



- Repeater spacing for commercial systems
  - Long-haul systems - 600 km repeater spacing
  - Ultra-long haul systems - 2000 km repeater spacing (Raman + EDFA amplifiers, forward error correction coding, fast external modulators)
  - Metro systems - 100 km repeater spacing
- State of the art in DWDM: channel spacing 50 GHz, 200 carriers, á 10 Gb/s, repeater spacing few thousand km

Timo O. Korhonen, HUT Communication Laboratory

Lessons learned

- Understand how optical fibers work
- You can determine link system bit rate when the parameters of transmitter, reveicer and fiber are known
- Understand how optical sources and sinks work
- You know the principles of fiber-optic repeaters

Timo O. Korhonen, HUT Communication Laboratory