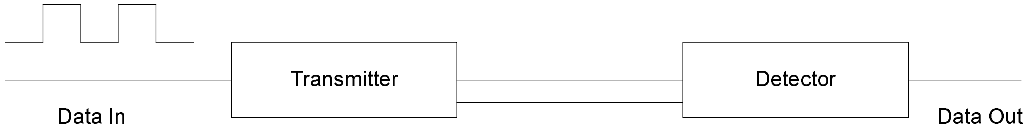
Optical links

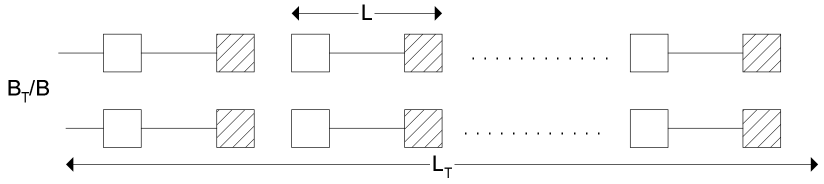


Technology is described by (B, L)
/ \
bps Km

Signal of B bps recovered at L Km with BER of 10^{-9}

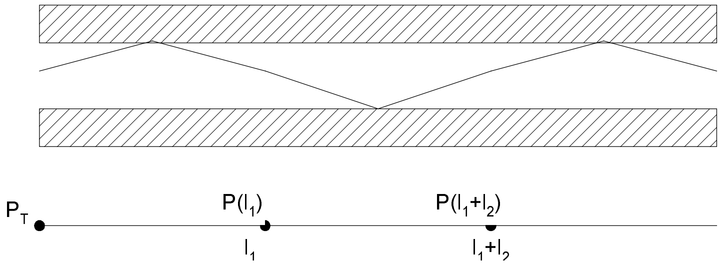
Suppose one wants to transmit B_T bps over L_T Km

One needs $\boxed{N_R = \frac{B_T \times L_T}{B \times L}}$ repeaters & links



Economically <u>the important figure is BxL</u> (bps x Km)

Fiber Attenuation



P_T = transmitted power

$P(l)$ = power at distance l

Let $P(l) = a(l)P_T$

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depends on wavelength and fiber

$$P(l_1+l_2) = a(l_1+l_2)P_T = a(l_2)P(l_1) = a(l_1)a(l_2)P_T$$

$$\Rightarrow a(l_1+l_2) = a(l_1)a(l_2) \Rightarrow a(l) = 10^{-\frac{Al}{10}}$$

A(dB/Km)=attenuation constant of fiber

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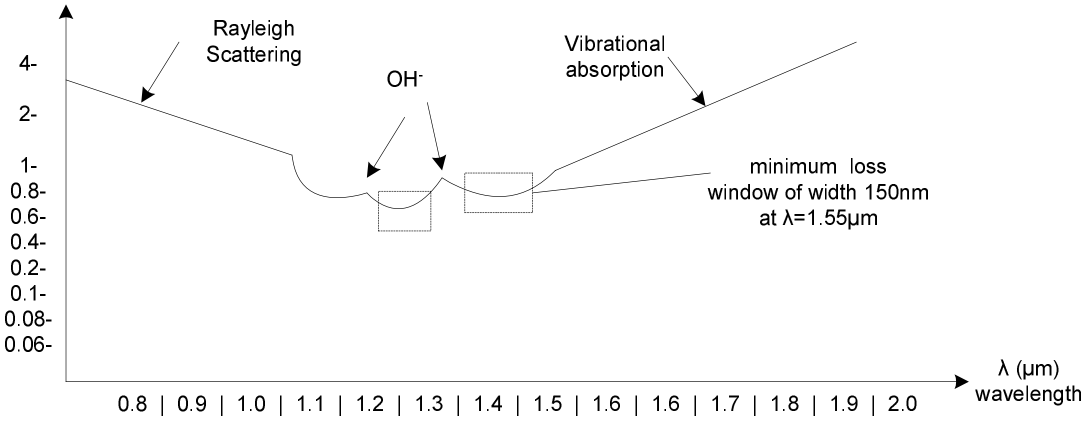
depends on wavelength λ & quality of fiber

Fiber Attenuation



low loss window of width
100nm at λ=1.33μm

The window at 1.33μm has a range of frequencies from $\frac{c}{\lambda + 100nm}$ to $\frac{c}{\lambda}$ (c=speed of light, λ=1.33μm) or 209.8 THz to 225.6 THz.

This window covers a range of 16THz ⇒ it can be used to transmit at about 8 Tbps (1.6 billion phone calls)

Example:

L = transmitter/receiver distance
P_T = transmitted power = 1mW
P_R = $10^{-4.5}$ mW = required received power for BER=10^{-9} at B=1Gbps
A = 0.2 $\frac{dB}{Km}$ = attenuation constant

Max length: $P_R = 10^{-\frac{AL}{10}} P_T$

$$\Rightarrow L = \frac{10}{A}\log_{10}\frac{P_T}{P_R} = 225Km$$

$\boxed{B \times L = 225Gbps \times Km}$ for optical fiber

Compare with coaxial cable: at

$$\left.\begin{aligned} &B = 100Mbps, A = 30\frac{dB}{Km} \\ &P_T = 1W, P_R = 10^{-7.5}mW \end{aligned}\right\} \Rightarrow L = 3.5Km \Rightarrow B \times L = 0.35Gbps \times Km$$

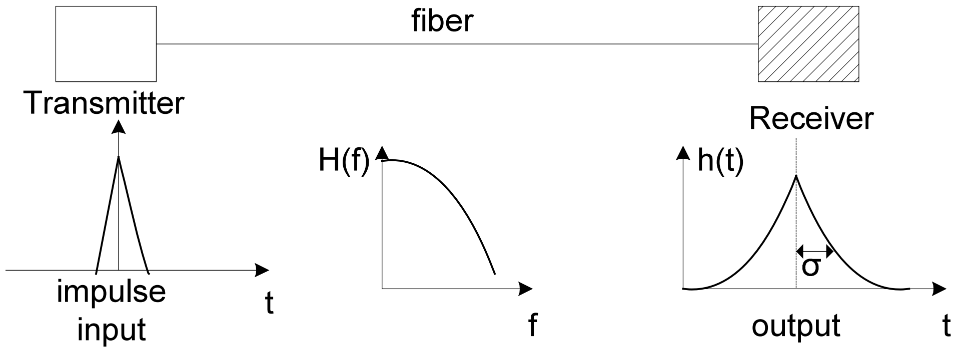
for coaxial cable

Note 1: L increases linearly in $\frac{1}{A}$ and logarithmically in P_T or P_R

Note 2: $P_R = \overline{N} \cdot B \cdot h\frac{c}{\lambda}$, λ=1.3μm

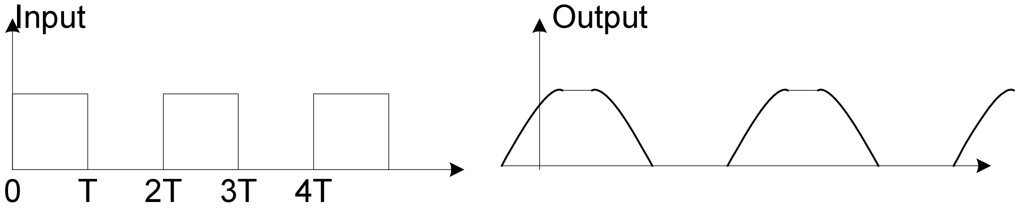
$\overline{N} = 1000 - 2000\frac{photons}{bit}$ for BER=10^{-9} and InGaAs PIN receiver

Fiber Dispersion



σ = aL (a depends on fiber)

Suppose input is 101010 with bit rate B=$\frac{1}{T}$

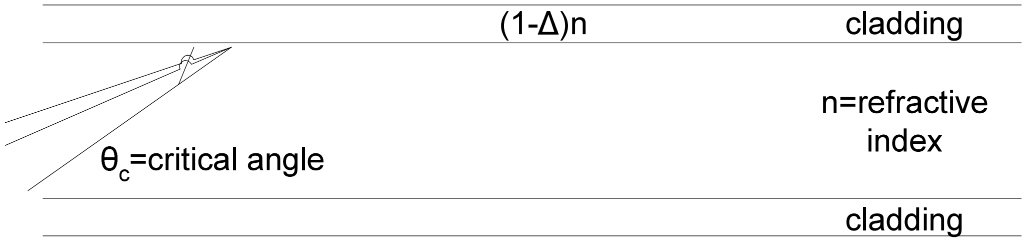


For dispersion not to result in errors we require, say, $\frac{\sigma}{T} < \frac{1}{4} \Rightarrow \sigma B < \frac{1}{4} \Rightarrow B \cdot L < \frac{1}{4a}$

Upper bound on BxL product due to dispersion

Dispersion limit together with attenuation limit determines the maximum usable length of a fiber for a given B.

Modal Dispersion in Multimode Fibers



$$\cos\theta_c = 1 - \Delta \Rightarrow \theta_c \approx \sqrt{2}\Delta$$

Different angles of propagation are called propagation modes

Different propagation modes travel different distances to go through L Km of fiber.

Distance traveled by propagation mode with angle θ is equal to L/cosθ, the time is $\frac{Ln}{\cos\theta \cdot c}$. The time difference between the fastest and the slowest component is

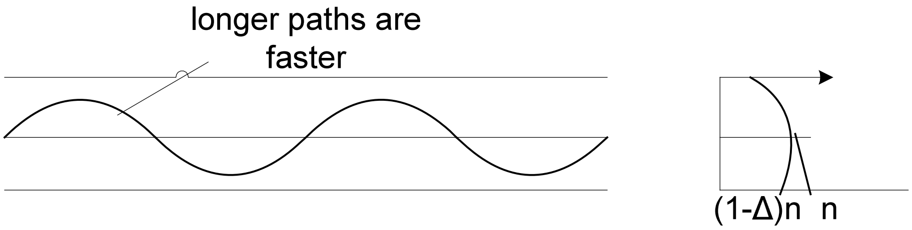
$$\frac{Ln}{c}\left(\frac{1}{\cos\theta} - 1\right) \approx \frac{Ln\Delta}{c} < \frac{T}{2} = \frac{1}{2B} \Rightarrow BL < \frac{c}{2n\Delta}$$

which is the upper bound on BxL product posed by modal dispersion

- Dispersion limit gives

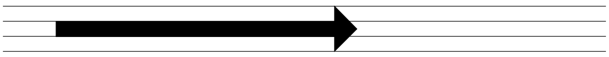
$$B \times L < \frac{c}{2n\Delta} = \frac{3 \times 10^5}{2 \times 1.46 \times 0.01} = 10 Mbps \times Km$$

- Dramatic improvement with graded index (GRIN) fibers



Can get $B \times L < \frac{2c}{n\Delta^2} = 4 Gbps \times Km$

- In <u>single mode fibers</u>, modal dispersion is absent since core diameter ≈ 8μm



<u>"Material" dispersion</u> present because refractive index is nonlinear function of λ

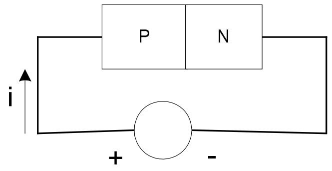
Analysis gives BxL < 250 GbpsxKm

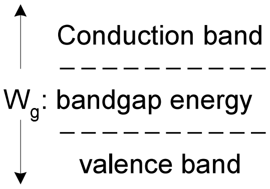
Sources

Requirements: low cost, reliability, power, coherence (phase/frequency), ability to be modulated

Two popular kinds of sources LEDs and LDs
/ \
light-emitting diodes laser diodes

LEDs





Light mechanism: recombination of electrons in conduction band with holes in valence band → excess energy emitted as a photon

$$\lambda = \frac{hc}{W_g} = \frac{1.24\mu m}{W_g(eV)}$$

$$W_g = a\frac{c}{\lambda}h$$

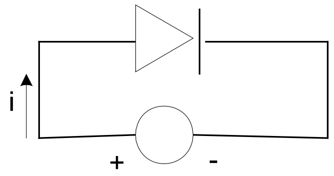
Material	λ(μm)	W$_g$(eV)
GaAs		1.4
AlGaAs	0.8-0.9	1.4-1.55
InGaAs	1.0-1.3	0.95-1.24
InGaAsP	0.9-1.7	0.73-1.35

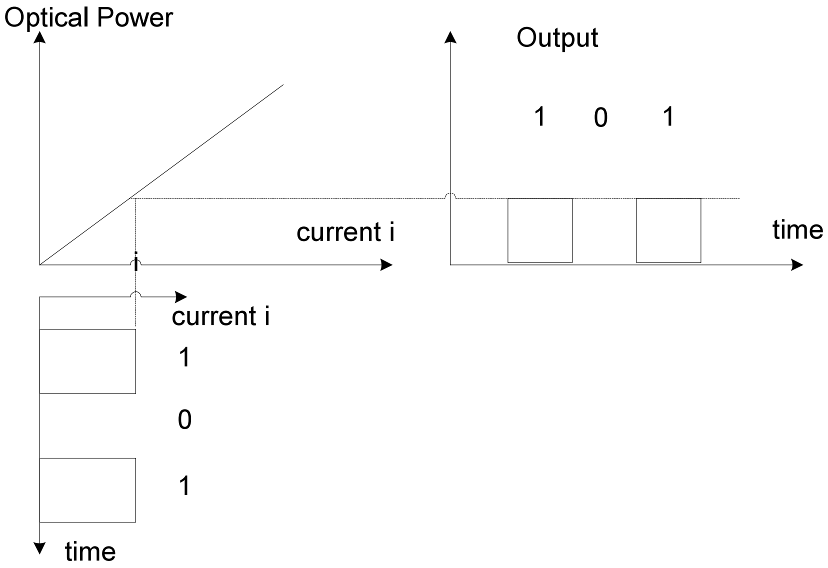
Optical power (mW): $P = niW_g$, $n = \frac{\#\,photons}{\#\,injected electrons}$

Typical power=1mW, Spectral width ≈ 100nm

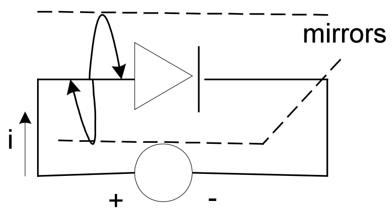
Light emitted is incoherent (different frequencies/ phases)

Modulation (Digital)





Laser Diodes (LD)



Light Mechanism:

Below threshold we have some phenomena as in LED

Above threshold we get “stimulated emissions”

Mirrors provide feedback to sustain stimulated emissions at certain wavelengths

Spectral width ≈ 3nm

Optical power: 1-10mW

Detectors

A detector has to determine whether '1' or '0'

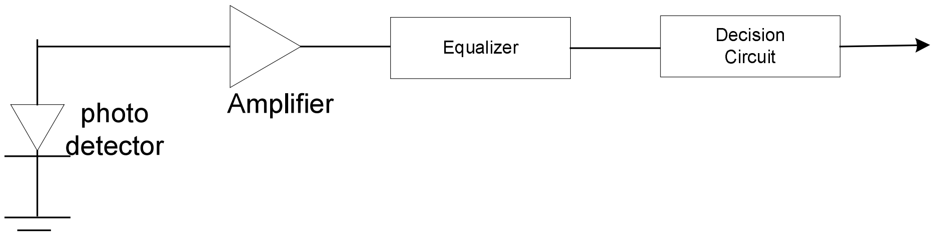
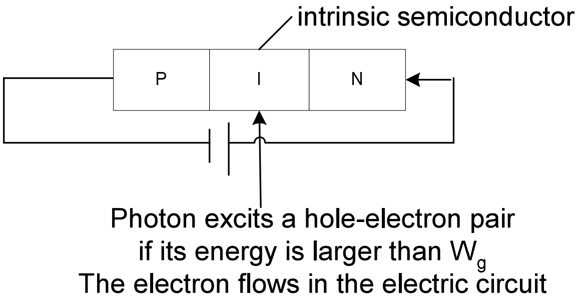


Photo detector is usually a PIN diode



Material of PIN diode is the same with that of LED or LD

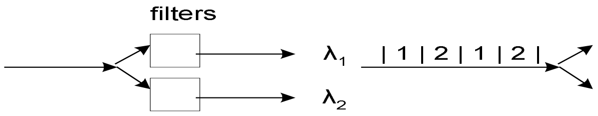
Current is proportional to number of arriving photons.

Sensitivity is reduced by "shot" noise.

All optical networks

Conventional switching at the network nodes require electron conversion (the electronic bottleneck), losing much of the benefit of optics.

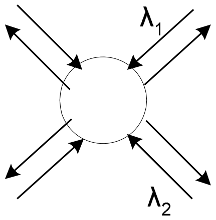
Network management and control require electronics, but all optical data paths is a reasonable goal with emerging optical technology.



Frequency division techniques are better developed than time division techniques for optical communication.

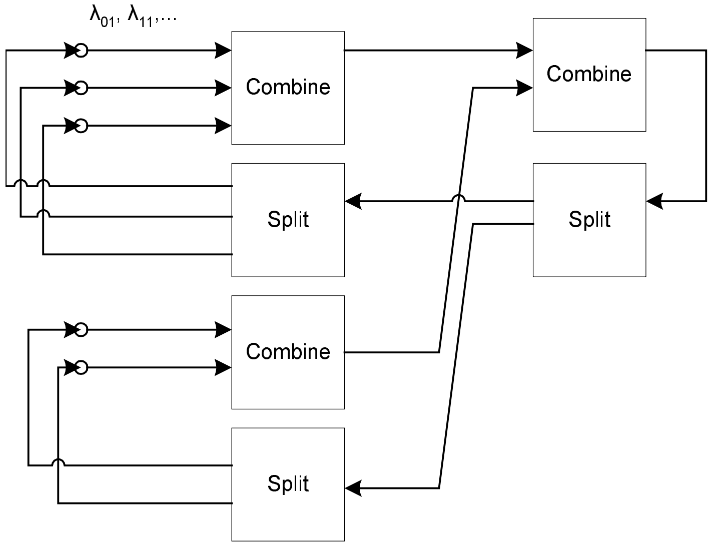
It is reasonably to multiplex F frequency channels on one optical fiber; for order of magnitude: F ≈ 100 channels, 1Gbps each.

“Optical Star” configuration



Each fiber has F ≈ 100 channels each at 1Gbps

Each of the N outgoing fibers carries the sum of all the incoming signals (attenuated by somewhat more than 1/N)



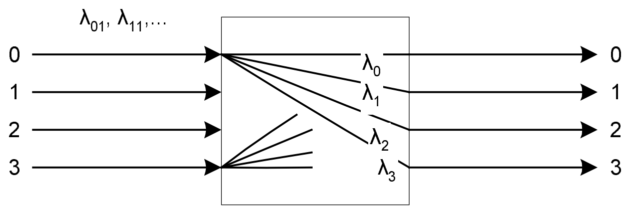
F point to point simultaneous connections are possible through the split

Tuning transmitters and receivers to same frequency and preventing drift are non-trivial

Limitation: everything goes everywhere; there is no spatial reuse of frequencies

Wavelength (λ) Router

Assume initially that the N frequency bands on each input fiber, λ_0, λ_1, ..., λ_n



The rule is that frequency λ_j on input port i, comes out at output port (i+j)mod n.

Output k receives n frequencies, one from each input port (i.e. frequency λ_j comes from (k-j)mod n).

Each frequency band λ_j, may have s subbands λ_{j1}, λ_{j2},...

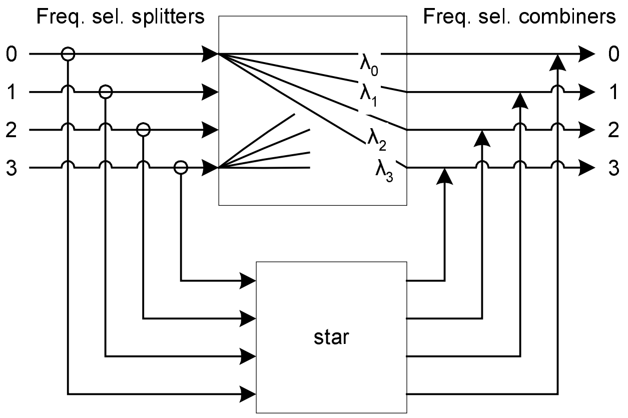
There is complete frequency reuse.

There is a lack of flexibility however (e.g. you cannot switch λ_0 from input port 0 to output port 1)

Lack of Flexibility

Two ways to deal with it:

- Create a dynamic router (appears to be very expensive)
- Create a star network bypass around λ router



The frequencies going through the star, so we see a tradeoff between capacity and flexibility.

Note: the frequencies going through the star can be used for applications that require broadcasting.

Other components

- Connectors (connects source to fiber)
- Power splitters
- Filters

} for optical switching

- Optical amplifiers