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Fiber Optic Communications

Optical Fibers.

- Fibers of glass
- Usually 120 micrometers in diameter
- Used to carry signals in the form of light over distances up to 50 km.
- No repeaters needed.

Optical Fibers.

- **Core** – thin glass center of the fiber where light travels.
- **Cladding** – outer optical material surrounding the core
- **Buffer Coating** – plastic coating that protects the fiber.

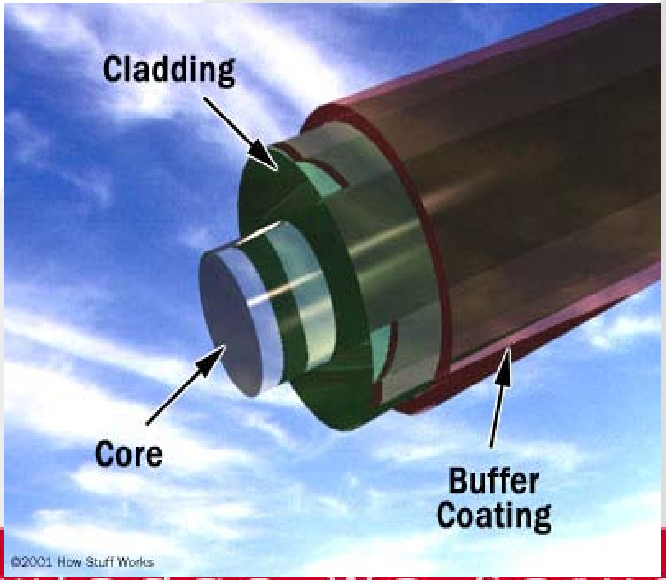
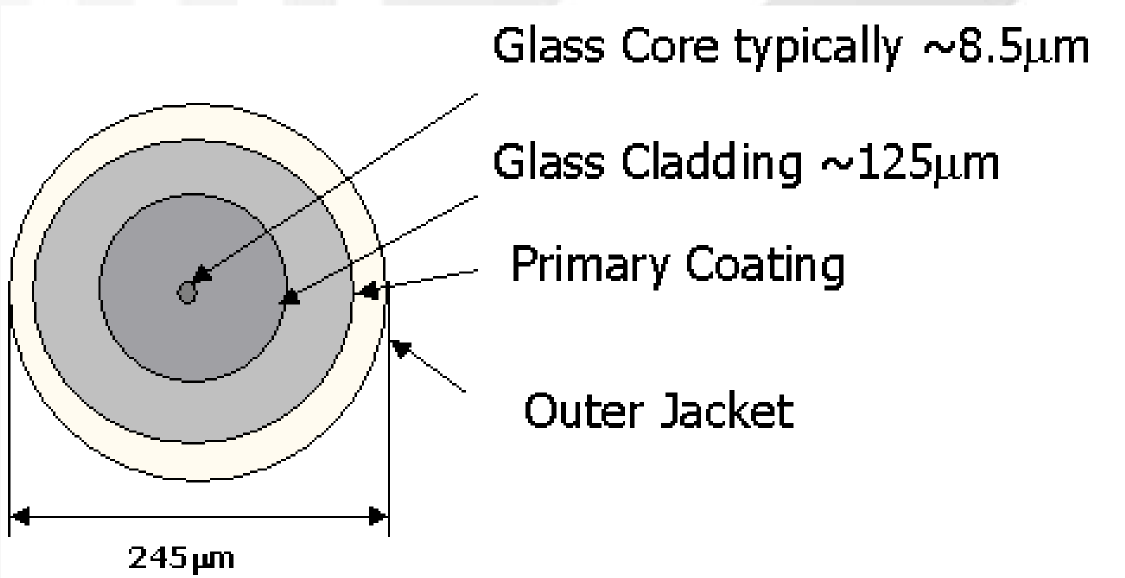


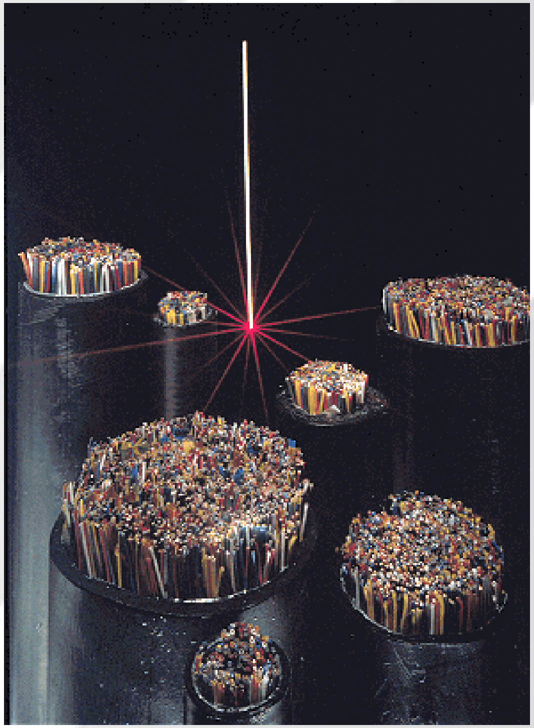
Figure of Merit for Transmission

- Bandwidth-distance product
- Throughput
- Bit error rate



Advantages

- Thinner
- Less Expensive
- Higher Carrying Capacity
- Less Signal Degradation
- Light Signals
- Non-Flammable
- Light Weight



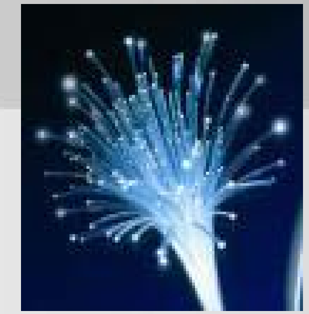
Evolution of Fiber

- 1880 – Alexander Graham Bell
- 1930 – Patents on tubing
- 1950 – Patent for two-layer glass wave-guide
- 1960 – Laser first used as light source
- 1965 – High loss of light discovered
- 1970s – Refining of manufacturing process
- 1980s – becomes backbone of long distance telephone networks in North America.

Areas of Application

- Telecommunications
- Local Area Networks
- Cable TV
- CCTV
- Optical Fiber Sensors

Type of Fibers

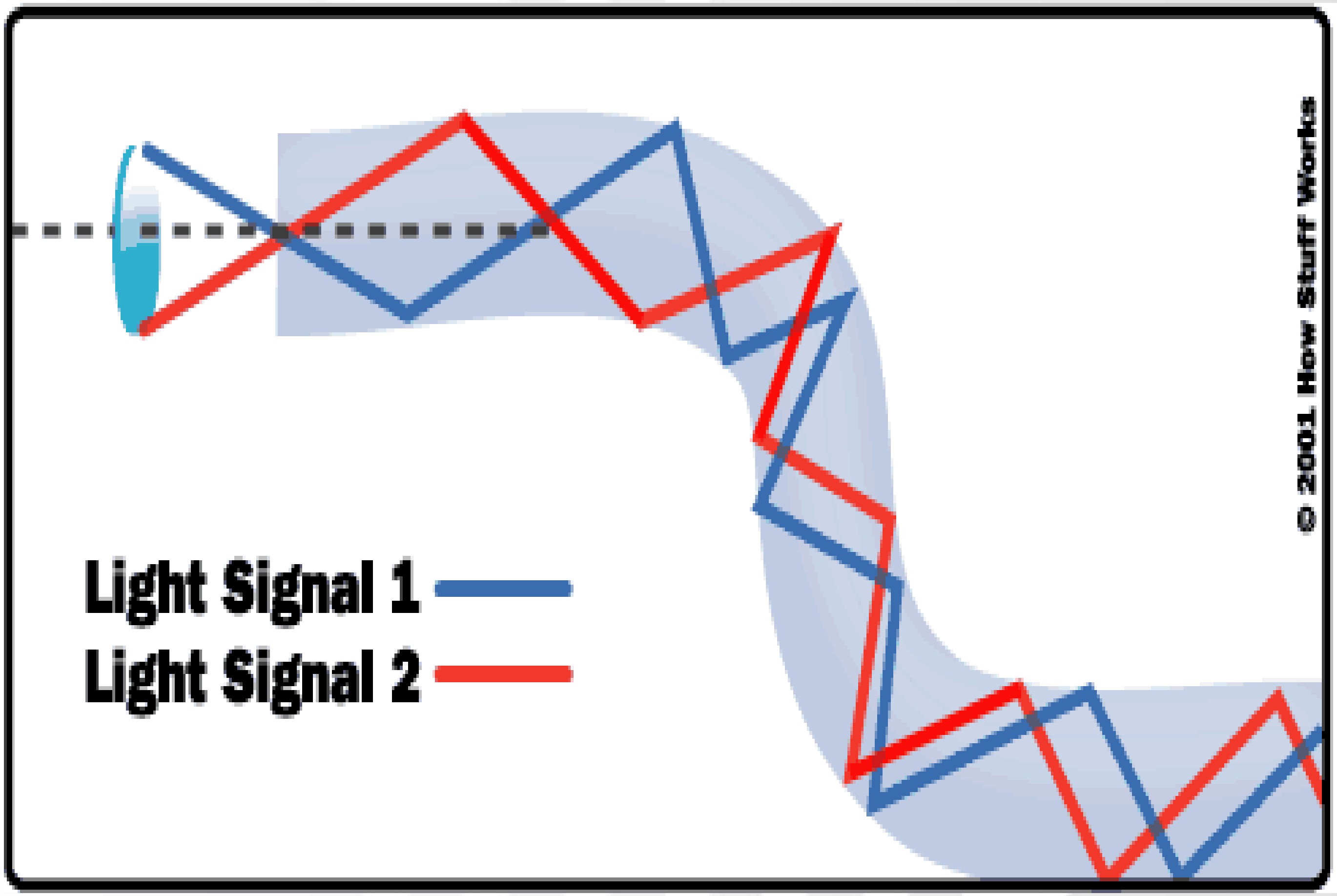


- **Single-mode fibers** – used to transmit one signal per fiber (used in telephone and cable TV). They have small cores(9 microns in diameter) and transmit infra-red light from laser.
- **Multi-mode fibers** – used to transmit many signals per fiber (used in computer networks). They have larger cores(62.5 microns in diameter) and transmit infra-red light from LED.

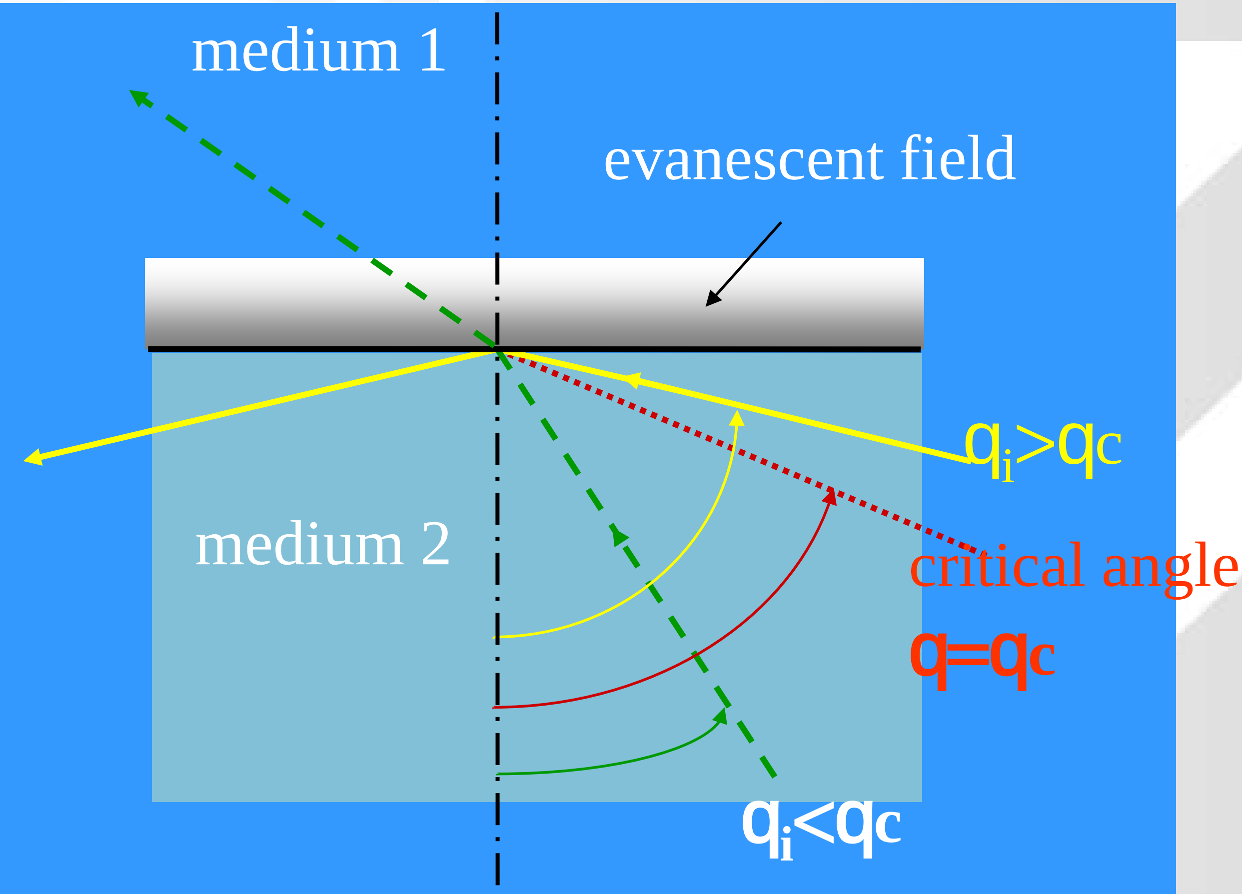
Working Principle

- Total Internal Reflection.
- Fibre Optics Relay Systems has
  - -Transmitter
  - -Optical Fibre
  - -Optical Regenerator
  - -Optical Receiver

Total Internal Reflection



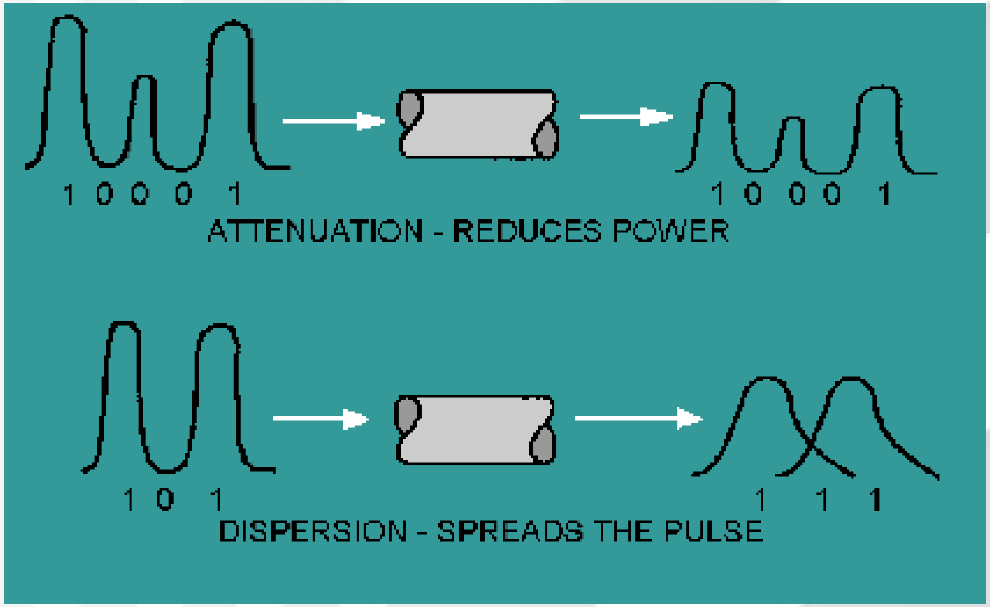
Total reflection

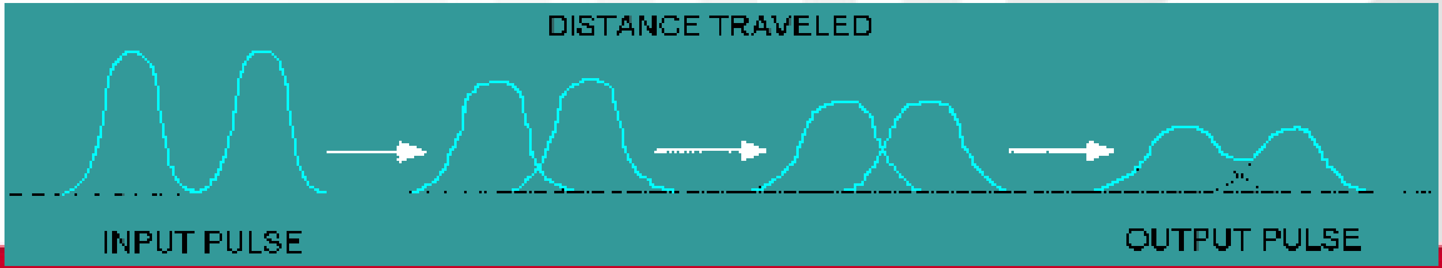


total reflection and evanescent wave

Attenuation and dispersion

- Attenuation: reduction of light amplitude
- Dispersion: deterioration of waveform





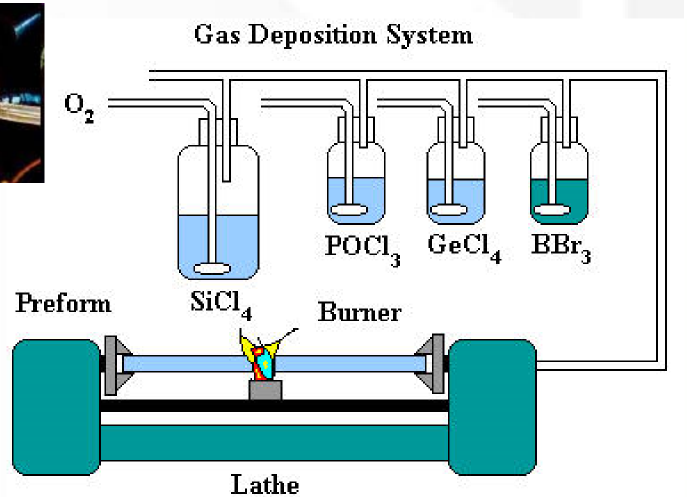
How are Optical Fibre's made??

- Three Steps are Involved

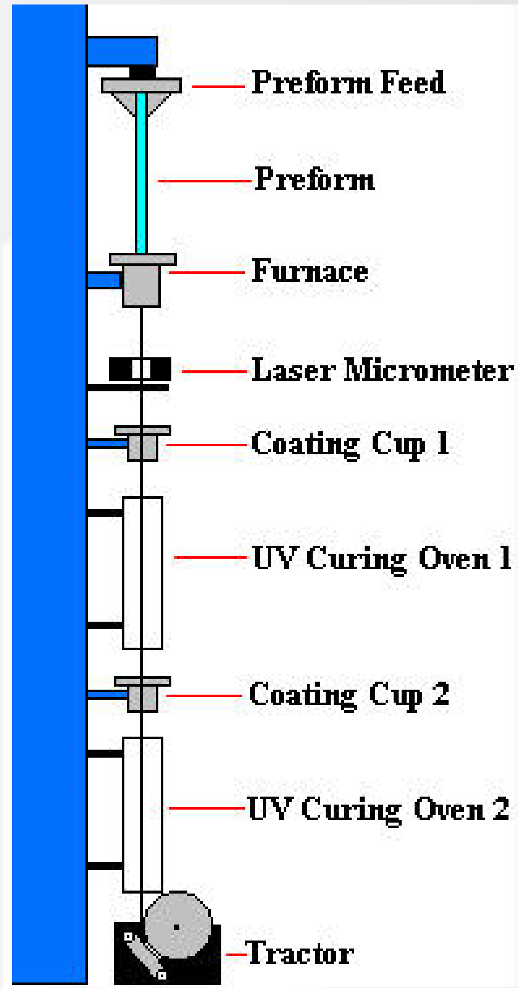
-Making a Preform Glass Cylinder

-Drawing the Fibre's from the preform

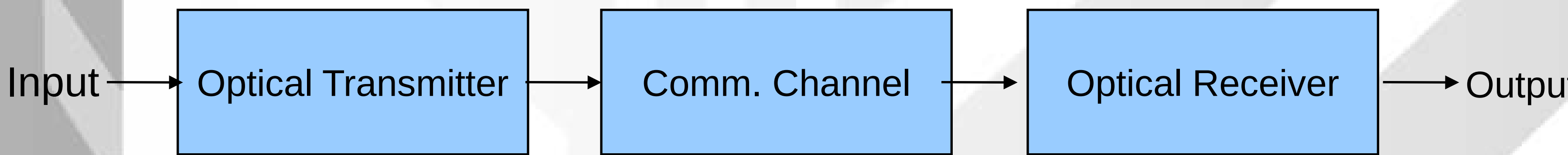
-Testing the Fibre


Gas Deposition System
O_2
$SiCl_4$
$POCl_3$
$GeCl_4$
BBr_3
Preform
Burner
Lathe


CORNING
OPTICAL FIBER


Preform Feed
Preform
Furnace
Laser Micrometer
Coating Cup 1
UV Curing Oven 1
Coating Cup 2
UV Curing Oven 2
Tractor

Generic Optical Comm. System



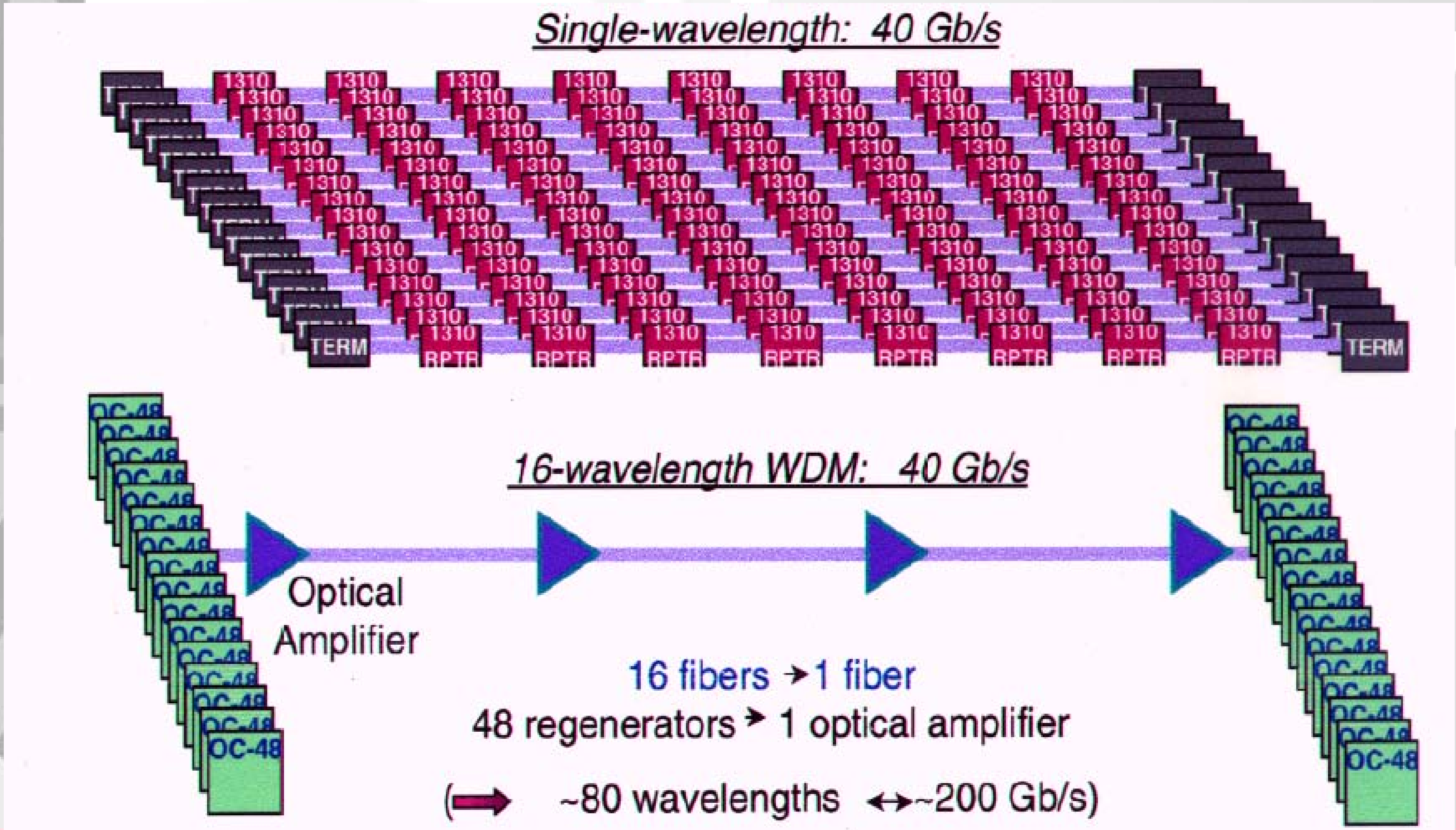
- Format
- Bandwidth
- Protocol

- Modulation Characteristics
- Power
- Wavelength

- Loss
- Dispersion
- 4-Wave Mixing
- Noise
- Crosstalks
- Distortion
- Amplification

- Bandwidth
- Responsivity
- Sensitivity
- Noise
- Wavelength

Wavelength Division Multiplexing



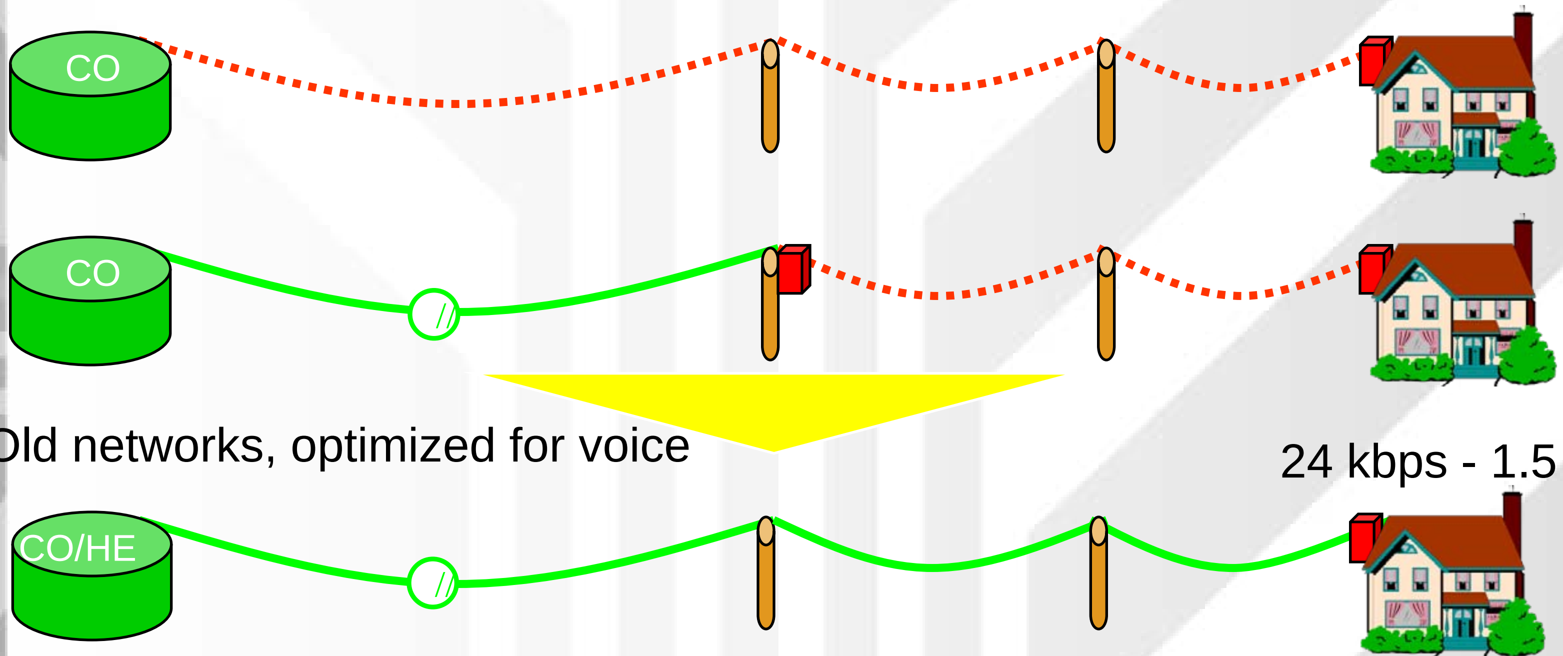
Fiber-to-the-Home

Definition

a telecommunications architecture in which a communications path is provided over optical fiber cables from the operator's switching equipment to the boundary of the home living space

Fiber-to-the-Home

Network Evolution From All-Copper to All-Fiber



Old networks, optimized for voice

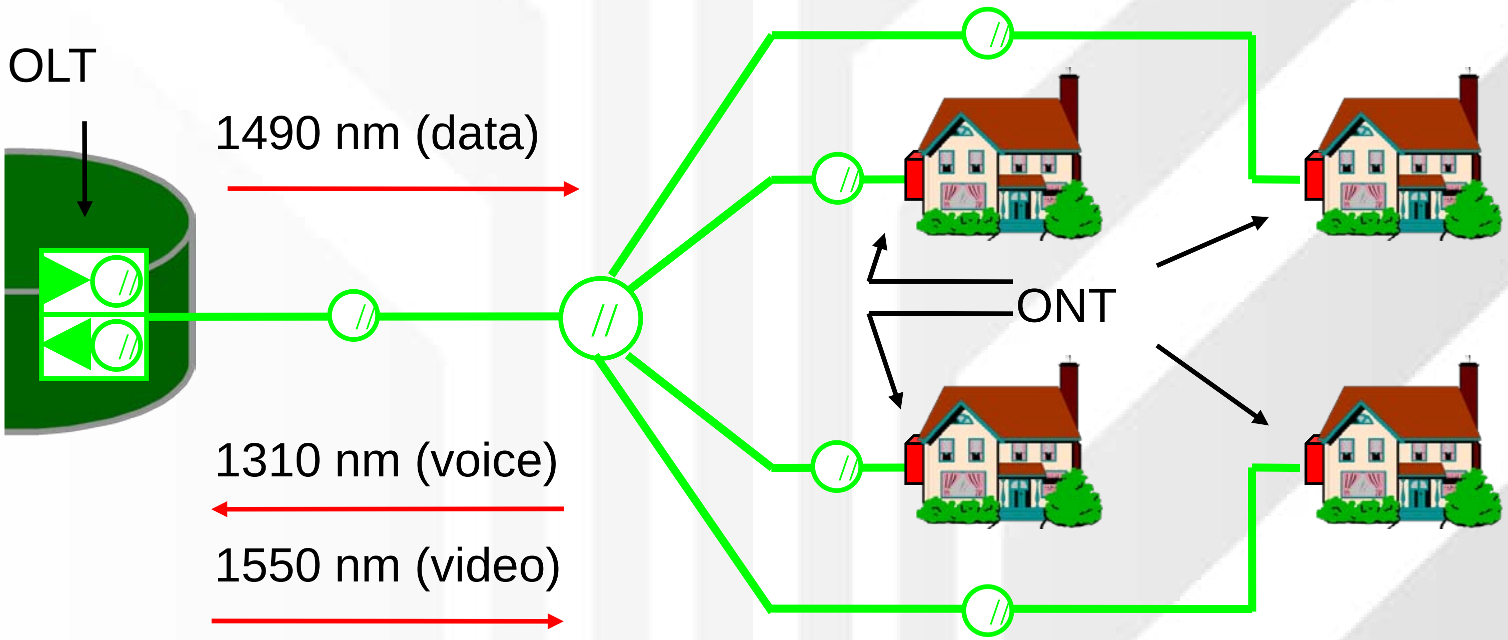
24 kbps - 1.5 Mbps

Optical networks, optimized for voice, video and data

19 Mbps - 1 Gbps +

Fiber-to-the-Home

Wavelength Allocation



Fiber-to-the-Home

Service Delivery Comparison

	Downstream Data Rate, Mbps	Upstream Data Rate, MBPS	Reach (K feet)
Satellite	0.400	0.028 – 0.056	-
Cable Modem (HFC)	1 - 10	0.1 - 1	1 - 6
ADSL (voice, data)	1.5 – 6.1	0.176 – 0.640	12 - 18
VDSL (voice, data, video)	13 - 52	0.64 - 3	1 - 6
Wi-Fi	11	1	>1
FTTH – PON	622	>155	60
FTTH - PtP	1000	1000	15 - 30

Fiber-to-the-Home

Voice (Telephone)

Data (Internet)

Video (SDTV, HDTV, Video-on-Demand)

Triple Play

Fiber-to-the-Home

Fiber to the Condominium Unit - Home Automation

Features of Home Automation

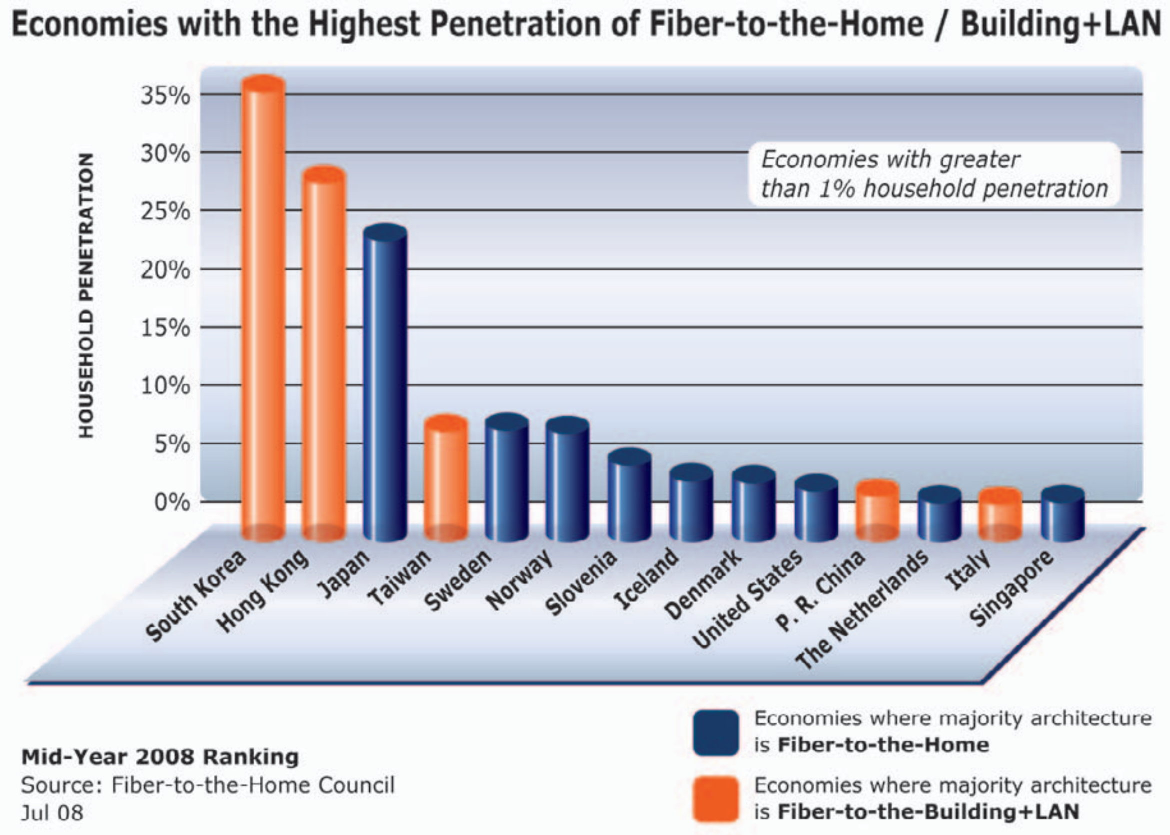
- Video Surveillance
- Lighting (including scene lighting)
- Heating and Air Conditioning
- Home Audio
- Home Video
- Pool Equipment and Water Features

Control your home from anywhere:

- Graphical touch screens
- Any Phone
- Any Computer

Fiber-to-the-Home

FTTH Penetration as of Mid 2008



References

[1] H. Kolimbiris, Fiber Optics Communications, Int. Edition, Pearson Education, 2004

[2] J. G. Proakis, Digital Communications, Fourth Edition, McGraw Hill, 2001

[3] J. C. Palais, Fiber Optic Communications, Fifth Edition, Pearson Education, 2005

[4] G. P. Agrawal, Fiber-optic Communication Systems, Third Edition, John Wiley & Son, 2002

[5] www.wikipedia.org

[6] www.youtube.com

"Light connects us"

Optical sources and amplifiers

Laser diodes

- Laser diodes are very similar to the structure of light emitting diodes.
- The main difference is the requirement of optical feedback to be able to establish laser oscillation.
- This is done by cleaving and polishing the end faces of the junction diodes to act as mirrors.

Laser diodes

- Qualitatively, the functionality of the laser diode can be described as follows :
  - Forward current injects holes and electrons into the junction.
  - Photons in the junction stimulate electron-hole recombination, with emission of added photons.
  - This process yields gain. If the gain exceeds the losses, oscillation occurs.
  - Therefore the gain must exceed a threshold value.
  - To obtain this threshold, the current must be greater than a certain value called the threshold current.

Laser diodes

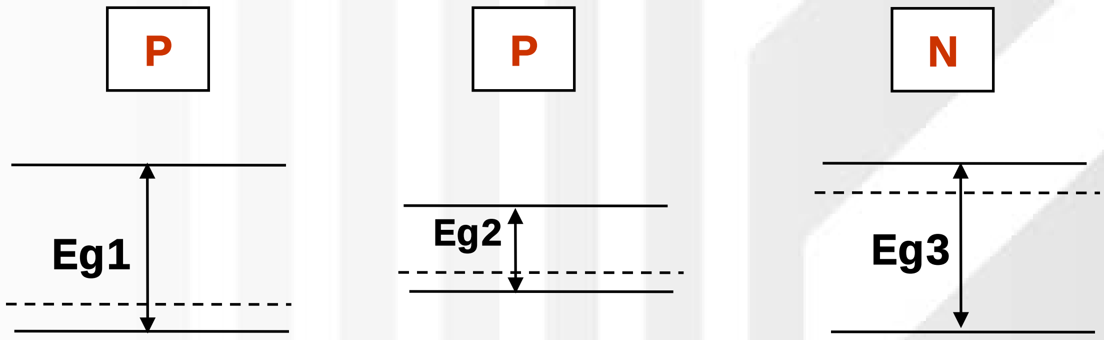
- **What are the sources of losses ?**
  - The losses happens because of absorption and in the case of the laser diode the spontaneous emission also contribute to losses indirectly
  - **WHY not like LED case ?**
  - In the case of the LED the spontaneous emission is the only source of light and it happens as the forward bias increases with a very low threshold voltage.
  - In this case there resonance due to cleaving of the LD walls which would attenuate most of the spontaneous emission since it is random and cannot be fixed at a certain wavelength and so the only outcome is the reduction of population inversion and lowering the efficiency resonance and stimulated emission

Homojunction vs. heterojunctions

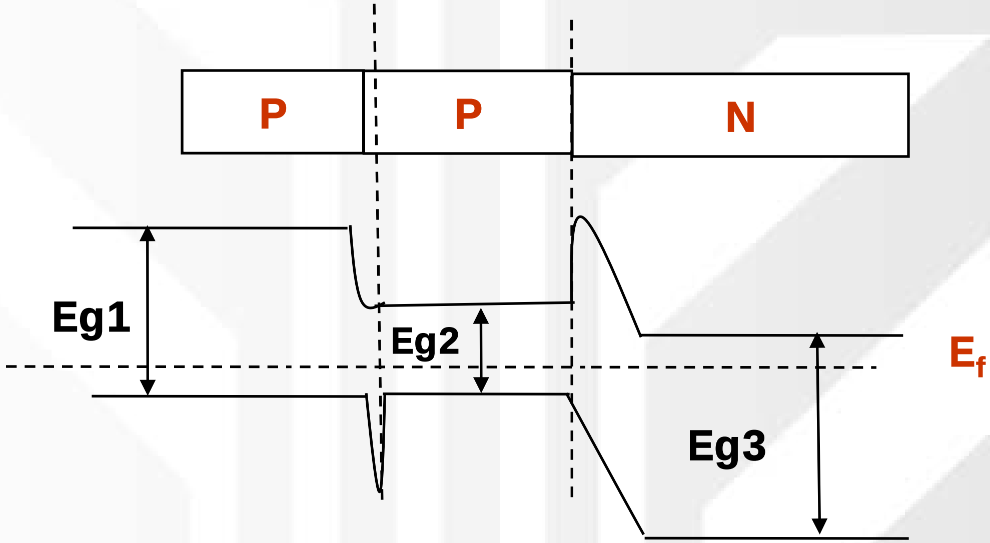
- The LED and the LD mentioned before were both described as homojunctions.
- A homojunction is a PN junction formed with a single semiconductor material.
- Homojunctions do not confine the light emitted very well as the junction is usually relatively large which causes light emission to be over a large angle and surface area which coupled to fiber very inefficiently.
- A heterojunction is a junction formed by dissimilar semiconductors.

Homojunction vs. heterojunctions

- Most LD are made of heterojunctions as they are much more efficient in light emission and in confinement of emission suitable for efficient coupling.
- This different materials will have different band gaps which can be designed to limit the distance over which the minority carrier may diffuse and also reduce the amount of absorption of generated photon.
- The figure below illustrate the band diagram of a double hetero-junction before connection



Functionality of heterojunctions

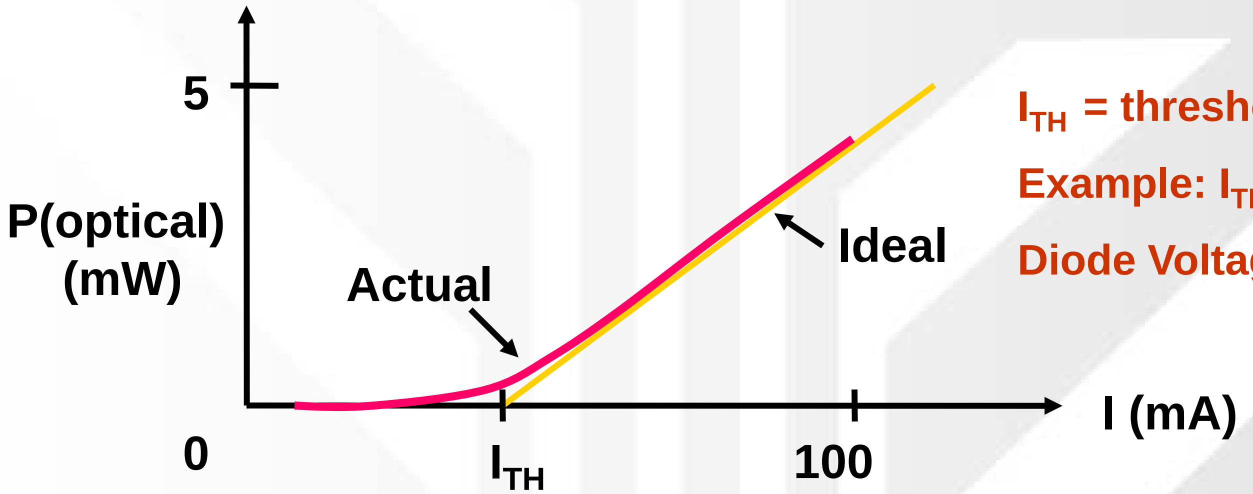


- When the structure is connected the Fermi level must remain constant for thermal equilibrium and because of the middle p-layer is smaller in band gap than the other two layers when the structure is forward biased electrons would flow to the middle p region but would be confined in that region since there is a potential barrier due to the difference in band gap limiting them from diffusing further in the adjacent p region.

Functionality of heterojunctions

- By keeping the middle layer extremely small (~0.1μm) the emitted photon can be confined to a very small area.
- Another advantage is that photons generated in other layers which move to the middle layer cannot be absorbed since it will have a different energy value than the band gap of the middle layer.

Laser diode operating characteristics



I_{TH} = threshold current

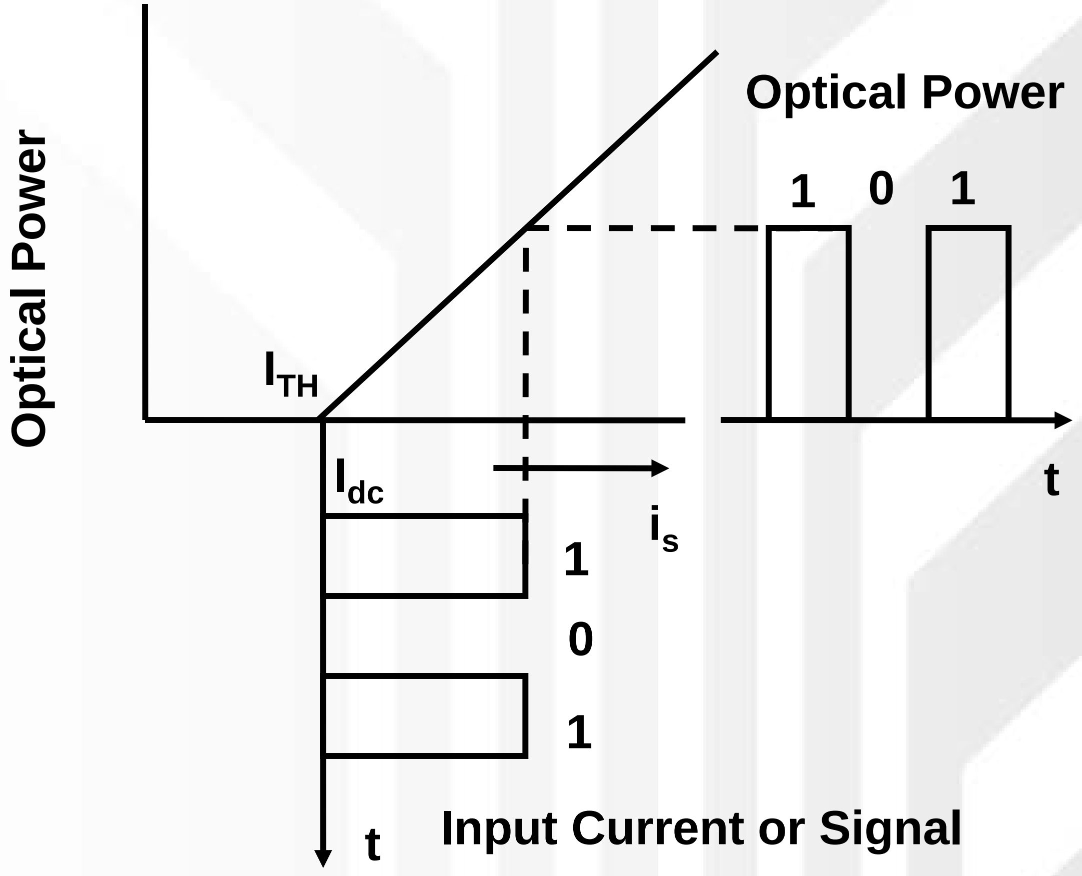
Example: I_{TH} = 75 mA

Diode Voltages ≅ 1.2 - 2 Volts

- **Below the threshold current there is a small increase in optic power with the drive current.**
- **This is non-coherent sponteneous emission in軡汭□e recombination layer. (Why so small?)**

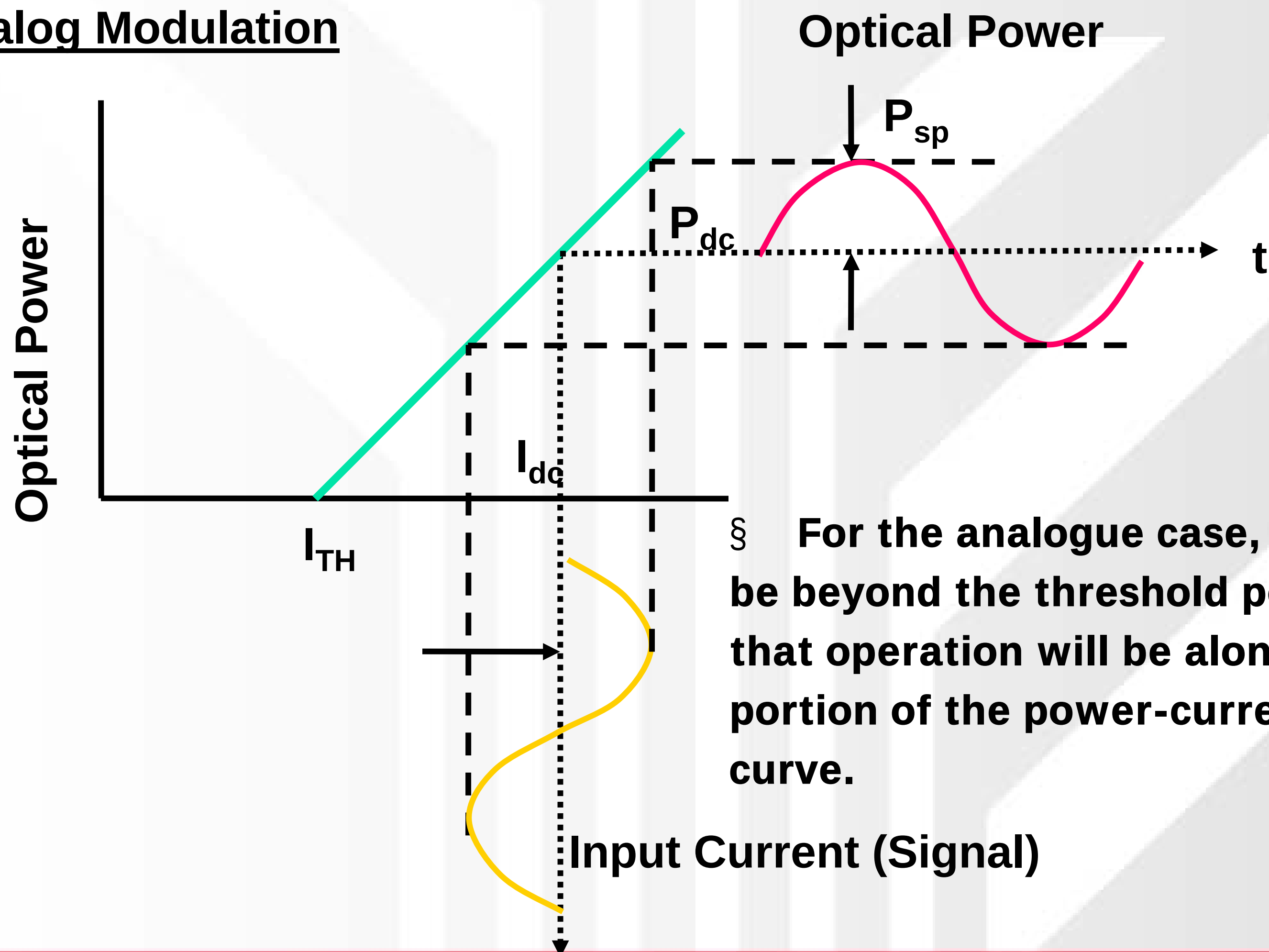
Digital modulation

Digital Modulation



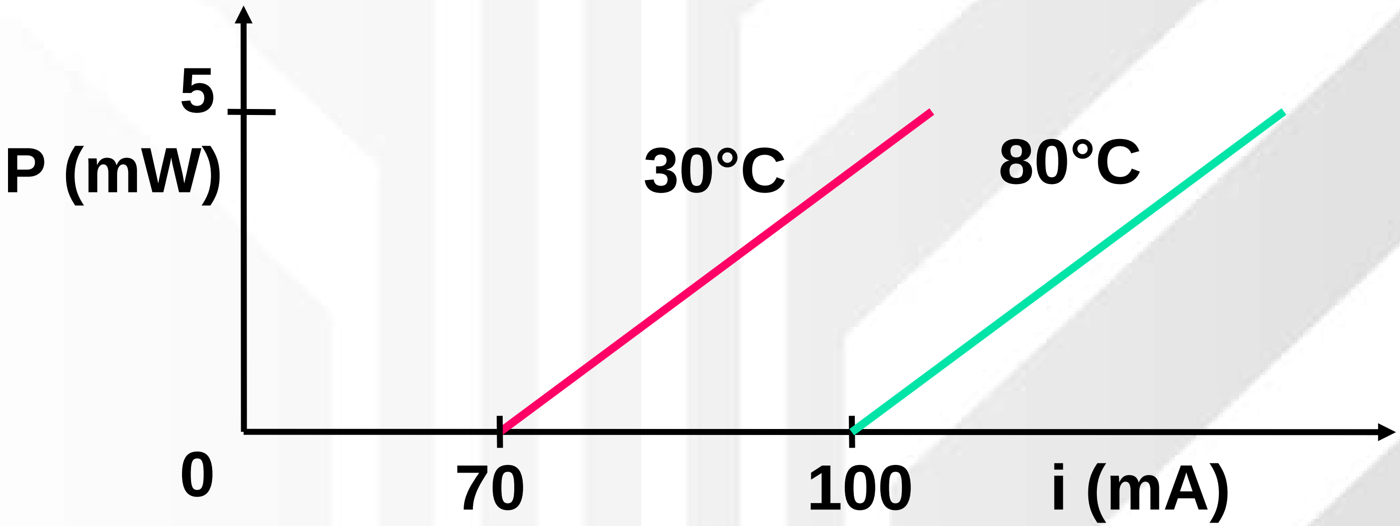
Analogue modulation

Analog Modulation



- For the analogue case, the dc bias must be beyond the threshold point to ensure that operation will be along the linear portion of the power-current characteristic curve.

Temperature dependence

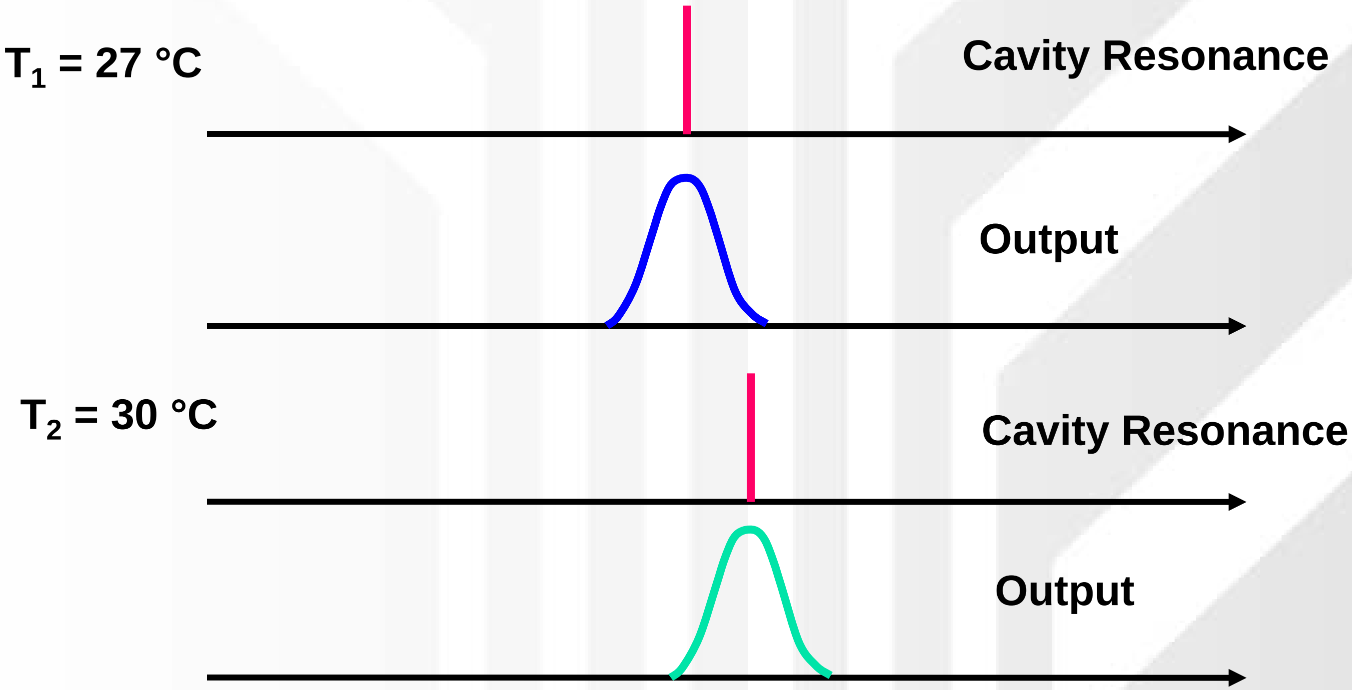


Temperature dependence

- As the temperature increases the diode gain decreases and so more current is required to overcome the losses and for oscillation to begin.
- The consequence is that the threshold current increases with the increase of temperature as shown in the previous figure.
- The reason for this happening can be explained as follows: increasing the temperature increase the energy of more electrons and holes to be free outside the active layer (in the n and p layers).
- More recombination happens outside the active layer with free carriers that would have reached the active layer but recombine instead.
- This reduces the number of charges reaching the active layer and consequently reducing stimulated emission and diode gain.
- In optical communication this might have drastic consequences as at constant current, if the temperature of the diode rises this will reduces the output power.
- Large reduction in power might increase detection error at the receiver and so reducing the overall performance of the communication system.

Laser wavelength dependence on temperature

- The wavelength is dependent on the temperature as consequence of the dependence of the refractive index of the material on temperature.
- Recall the cavity resonant frequency is given by : $f = \dfrac{mc}{2Ln}$



Laser spectral widths

- Laser diode typically posses line width between 1-5nm which is much smaller than that of an LED.
- Unlike the HeNe gas laser, in this case the emitting transition is happening in a semiconductor which occurs between energy bands not distinct lines as the case in gases.
- Therefore the line width is larger than that of a HeNe laser (which is typically of the order of 10^{-3} nm).

Laser spectral widths

- The cavity also affects the output spectrum. The cavity dimension can cause many longitudinal modes to co-exist.
- **Recall :** the cavity resonant wavelength spacing is given by :

$$\boxed{\Delta\lambda_c = \frac{\lambda_o^2}{c}\Delta f_c}$$

Where : $\Delta f_c = \dfrac{c}{2Ln}$

Thus

$$\Delta\lambda_c = \frac{\lambda_o^2}{c}\frac{c}{2Ln} = \frac{\lambda_o^2}{2Ln}$$

Laser spectral widths example

Assume:

λ_0 **= 0.82 μm, L = 300 μm, n = 3.6**

Δ λ = 2 nm (laser linewidth)

Then

$$\Delta\lambda_c = \frac{(0.82)^2}{2(300)3.6} = 3.11\times 10^{-4}\ \mu m = 0.311 nm$$

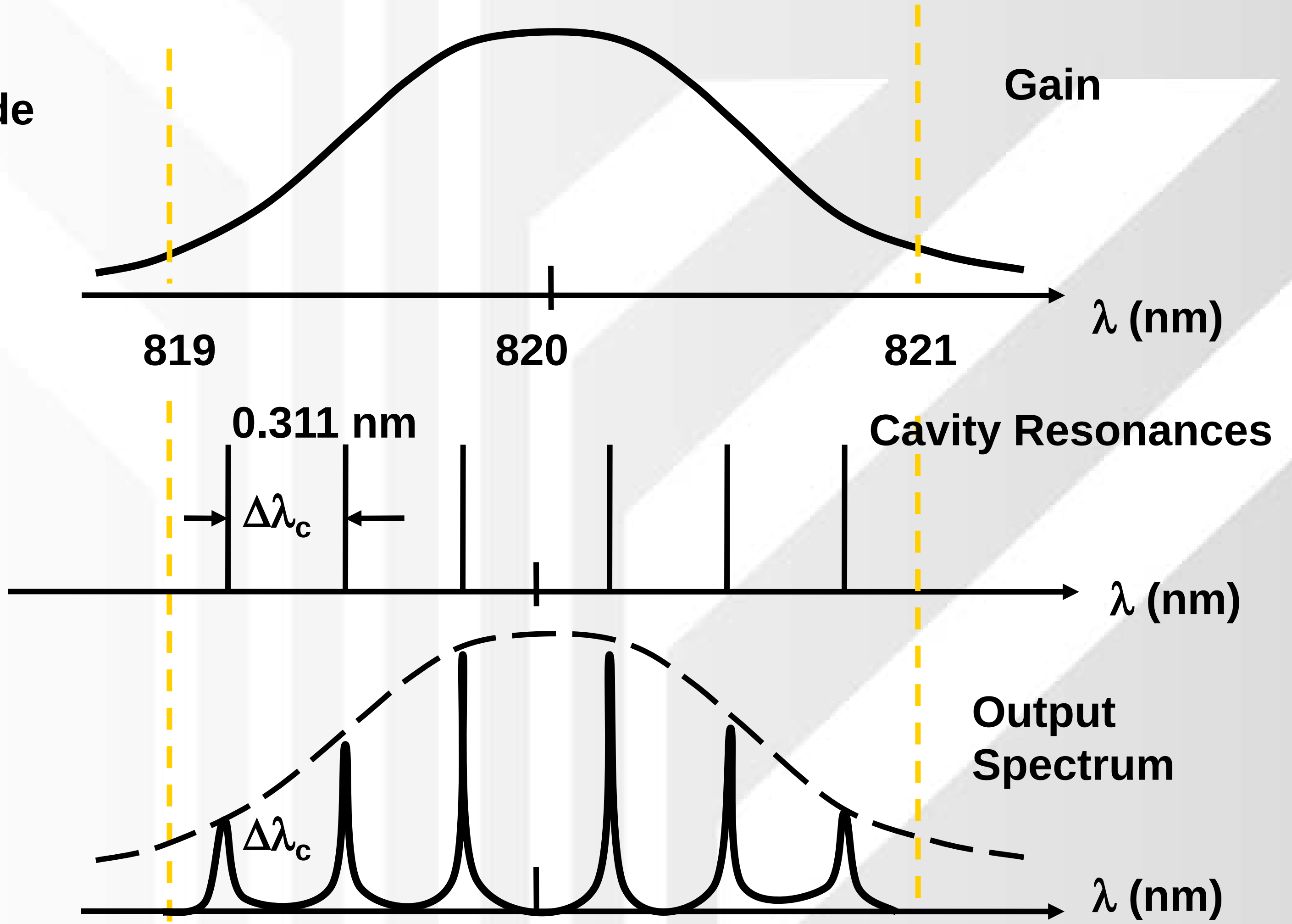
The number of longitudinal modes is approximately

$$N_m \cong \frac{\textbf{linewidth}}{\textbf{resonance spacing}} = \frac{\Delta\lambda}{\Delta\lambda_c}$$

$$N_m = \frac{2nm}{0.311nm} = 6.4 \cong 6$$

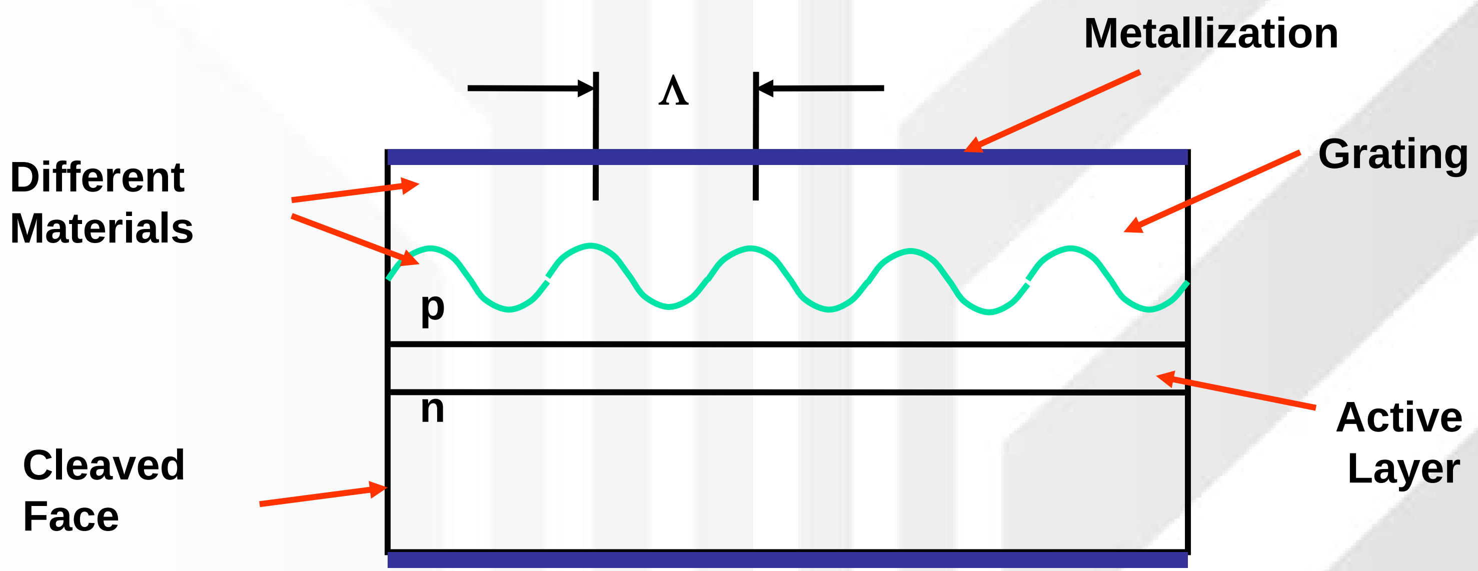
Plot of the laser modes

For the laser diode we have:



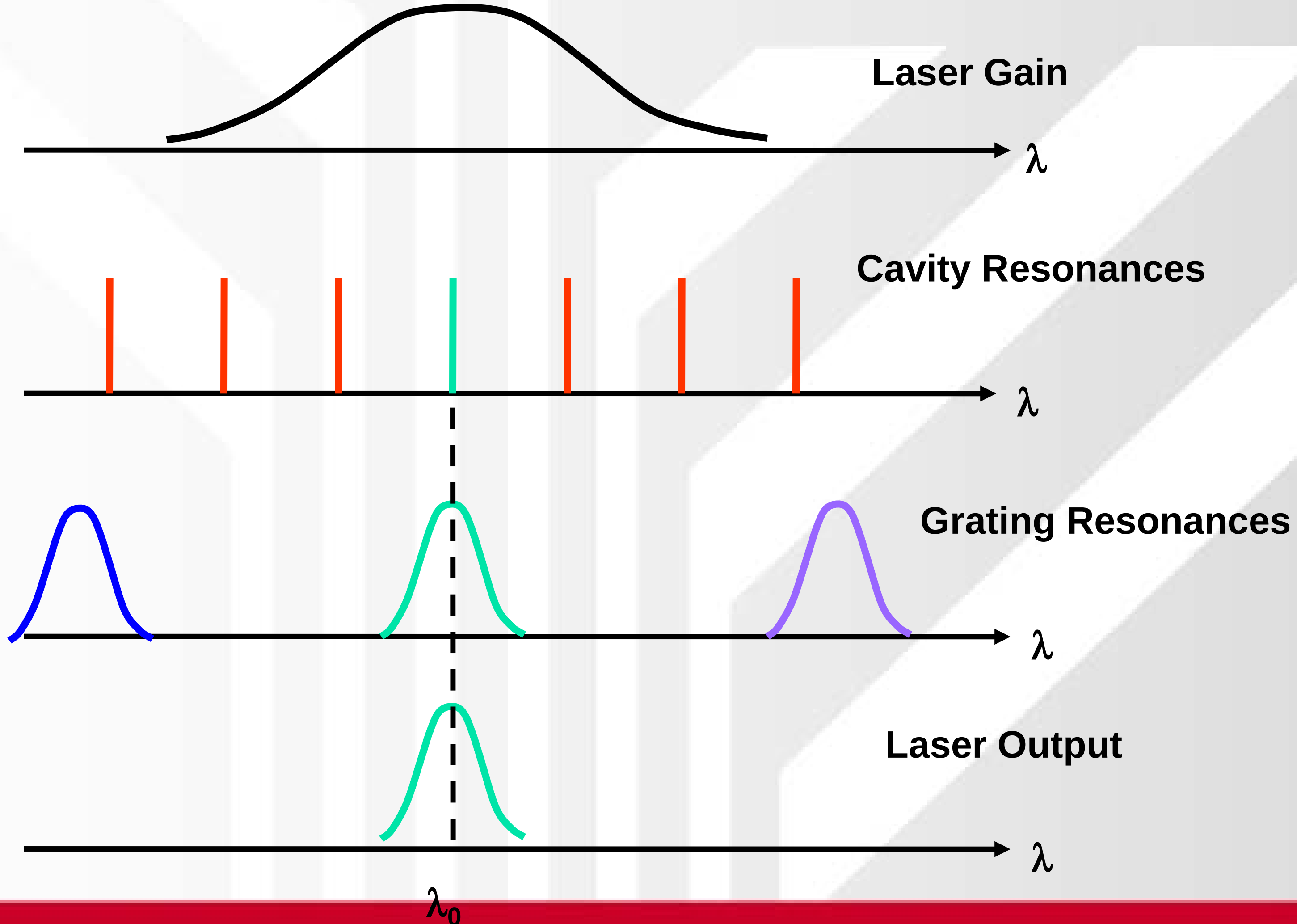
Distributed feedback laser diode

- Distributed feedback (DFB) lasers is a type of laser which produces very narrow linewidth (single longitudinal mode laser).
- The figure below shows the structure of a DFB laser from inside.



The grating (etched just above the active layer) acts as a wavelength selective filter, permitting only one of the cavity's modes to propagate.

Distributed feedback laser diode



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Distributed feedback laser diode

- The grating resonances, according to Bragg's law, are those wavelengths for which the grating period Λ (illustrated on a preceding slide) is an integral number of half-wavelengths. That is:

$$\Lambda = \frac{m\lambda}{2}$$

- λ is the wavelength in the diode, m is an integer

$$\lambda = \frac{\lambda_0}{n}$$

- λ_0 is the free-space wavelength
- The grating period then satisfies :

$$\Lambda = m\left(\frac{\lambda_0}{2n}\right) \rightarrow \boxed{\lambda_0 = \frac{2n\Lambda}{m}}$$

Distributed feedback laser diode

Example: Consider an InGaAsP DFB LD

λ_0 = 1.55 μm, n = 3.5, let m = 1 (first order)

Determine the grating period.

$$\Lambda = \frac{m\lambda_0}{2n} = \frac{1.55}{2(3.5)} = 0.22\,\mu m$$

Let m = 2 (second order)

$$\Lambda = \frac{m\lambda_0}{2n} = \frac{2(1.55)}{2(3.5)} = 0.44\,\mu m$$

Tunable laser diodes

- There is a need in fiber systems for sources which can be tuned to precise wavelengths. The most common examples are the WDM systems, where a number of closely spaced wavelengths are needed to provide multiple carriers on the same fiber.
- One possibility is to tune a DFB LD by changing its temperature or its drive current (which changes its temperature). Tuning is on the order of 10^{-2} nm/mA.

Tunable laser diodes

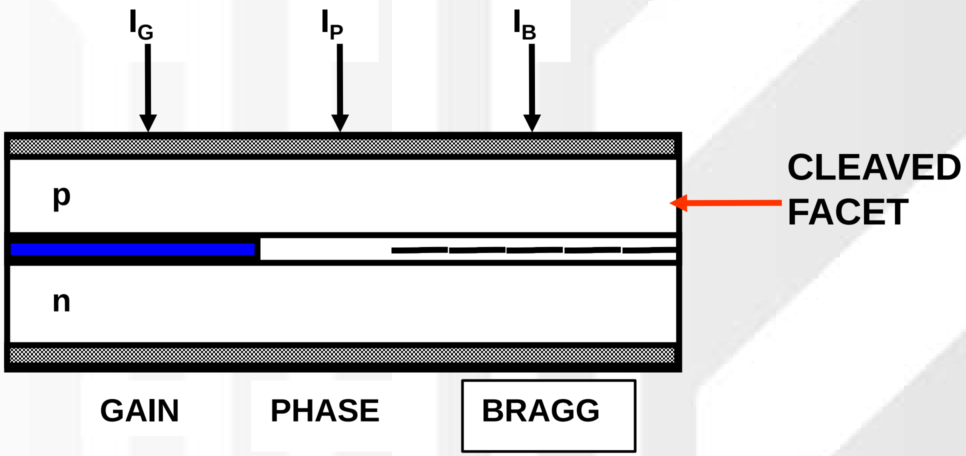
- This can be useful but if we want to use it as a WDM source this will not be practical as typical WDM systems will need tunability in the range of 10nm or more.
- For this reason another variation of the DFB LD can be used which called distributed bragg reflector laser diode.

DBR laser diode

- In a DBR LD there are three regions : the gain, the Bragg and the phase.
- Each region is supplied with a separate currents as shown in the diagram.
- The gain current (I_G) determines the amplification in the active region and so the level of the output power.

DBR laser diode

- The phase current (I_P) act as a control of the feedback from the bragg reflection by changing the phase of the wave reflected from the Bragg region through heating the phase layer which changes its refractive index.
- The current (I_B) control the Bragg wavelength by changing the temperature in the Bragg region which again changes the refractive index.



DBR laser diode

- The operating wavelength, can be given by : $$\boxed{\lambda_0 = 2n_{eff}\Lambda}$$
- assuming the first order resonance (m=1), and λ_0 is the free-space emitted wavelength, and n_{eff} is the effective refractive index.
- The tuning range ($\Delta\lambda$) is proportional to the effective refractive index variation (Δn_{eff}).

$$\boxed{\frac{\Delta\lambda}{\lambda} = \frac{\Delta n_{eff}}{n_{eff}}}$$

- If the center wavelength is 1500 nm, the tuning range would be 15 nm.

Optical amplifiers

- Fiber optic systems are mainly limited by either bandwidth or attenuation.
- If we are transferring a digital signal via a fiber optic link a regenerator can be inserted in the middle if the link is too long and the signal is severely attenuated.
- The regenerator detects the optical signal , converting it to the electrical form, detects the ones and zeros and removes the pulse spreading and distortions then reconverts the signal to an optical form to be resent via the optical link.

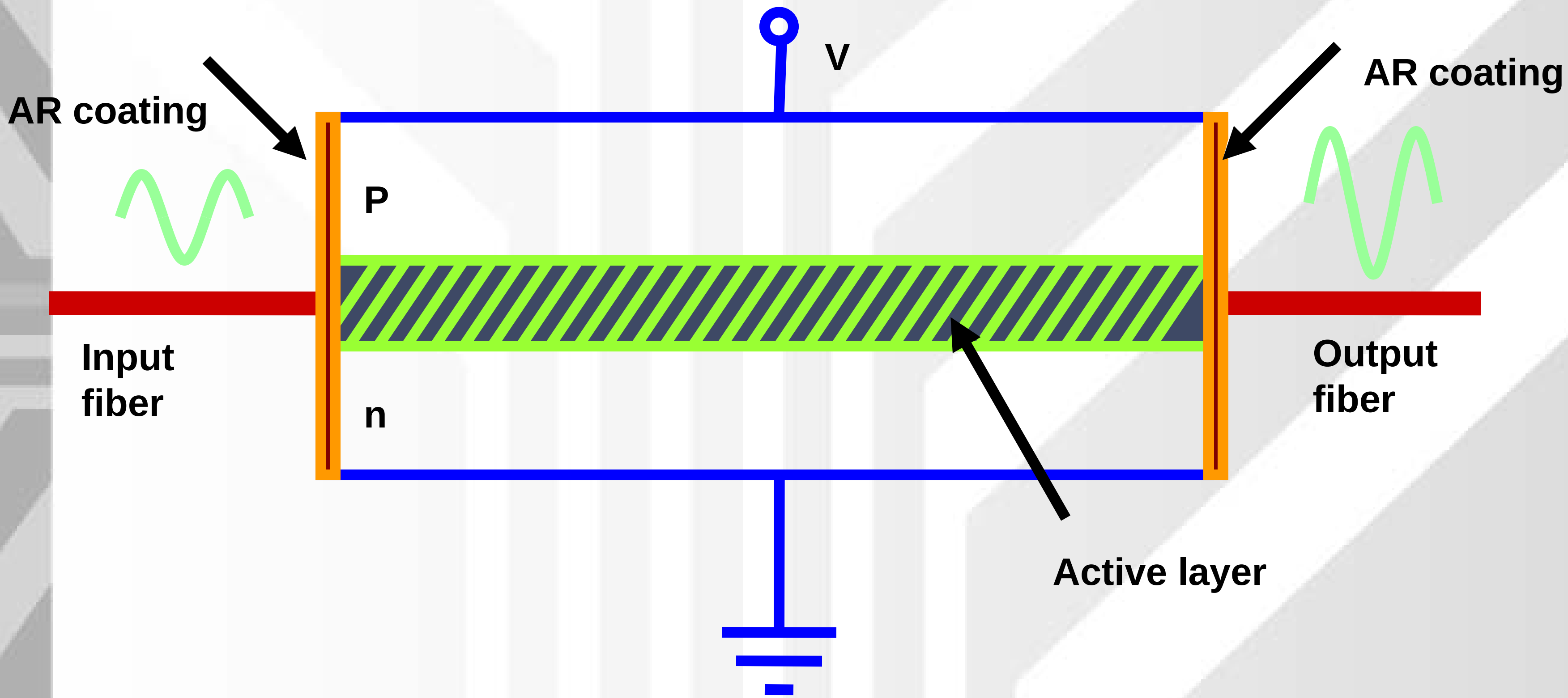
Optical amplifiers

- In an analogue signal the situation is more difficult but still possible.
- Both these methods have been actually successfully implemented in the past for cross-Atlantic transmission for example.
- However, these methods are expensive in all its stages (construction , installation, require large power etc ...)
- This was the motivation behind trying to find an all optical amplifier which saves the double conversion OEO along transmission every time we need to amplify the signal.

Optical amplifiers

- From the discussion of laser principles it was clear that the laser operation include some kind of amplification of light.
- Essentially this means operating laser without mirrors or with mirrors but below the bias threshold (as the input light needs to be the cause of stimulation instead of inducing photons through increasing the driving current which would distort the signal.)

Optical amplifiers



Optical amplifiers

- In practice, several problems came up when these structures were used which limited the efficient use of semiconductor amplifiers

- Problems:
    1. Low gain
    2. High noise
    3. Polarization dependent gain
    4. Low coupling efficiency to the fiber
  - The solution to the problems of the semiconductor amplifier is the erbium-doped-fiber amplifier (EDFA) which is explained next

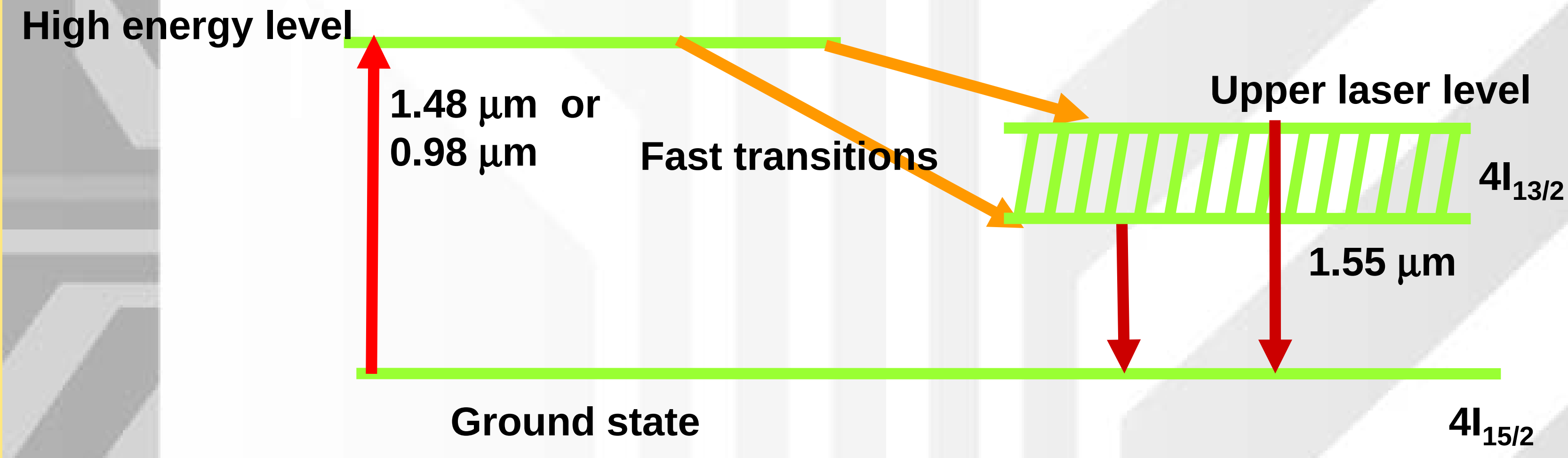
Erbium doped fiber optical amplifier

- ***Erbium doped fiber amplifier*** is an effective optical amplifier because of its :
  - High gain **(15 dB or more).**
  - Wavelength of amplification is the 1550nm which cause very low loss during transmission.
  - Low noise.
  - Low drive power consumption **(400 mA, 2 volts, 0.8 watts)**
  - Wide bandwidth (20 to 30 nm).
  - Amplifier works for digital and analog systems.
  - Multiple channels (WDM) can be amplified simultaneously.

Erbium doped fiber optical amplifier

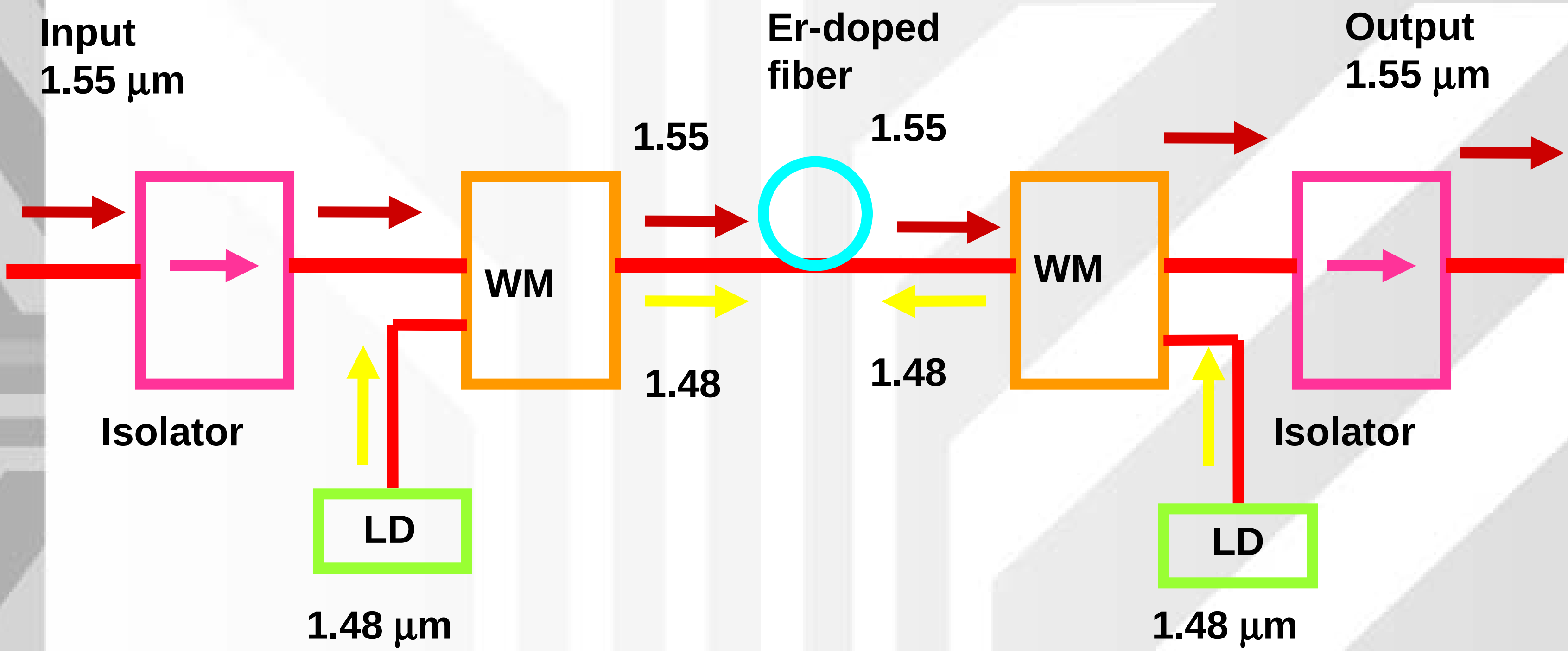
- **Operation of EDFA : (two light beams pump light and signal light)**
- Pump photons (1.48 mm or 0.98 mm) are absorbed raising the Erbium atoms to the high energy level.
- The atoms decay, non - radiatively, to the upper laser level.
- That level has a long lifetime, so the atoms remain in that state until incoming photons (in the 1.55 mm range) stimulate transitions to the ground state.
- The stimulated transitions produce photons with the same wavelength and phase of the stimulating photons and so causing amplification.

Erbium doped fiber optical amplifier



Erbium doped fiber optical amplifier

EDFA Configuration (Practical)



- Pumping in both directions increases the total gain.
- Isolators keep the amplifier from going into oscillation.

Noise figure

- Any amplifier not only increases the signal, it also increases the noise.

- In an ideal amplifier, both are increased by the same factor. In this case, the signal-to-noise ratio at the amplifier output is the same as at its input.

- Real amplifiers add noise, so that the SNR is less at the output than at the input.

Noise figure

- The signal is degraded by the amplifier. The *noise figure* F is a measure of this degradation.
- The noise figure is given by:

$$F = \frac{(S/N)_{in}}{(S/N)_{out}}$$

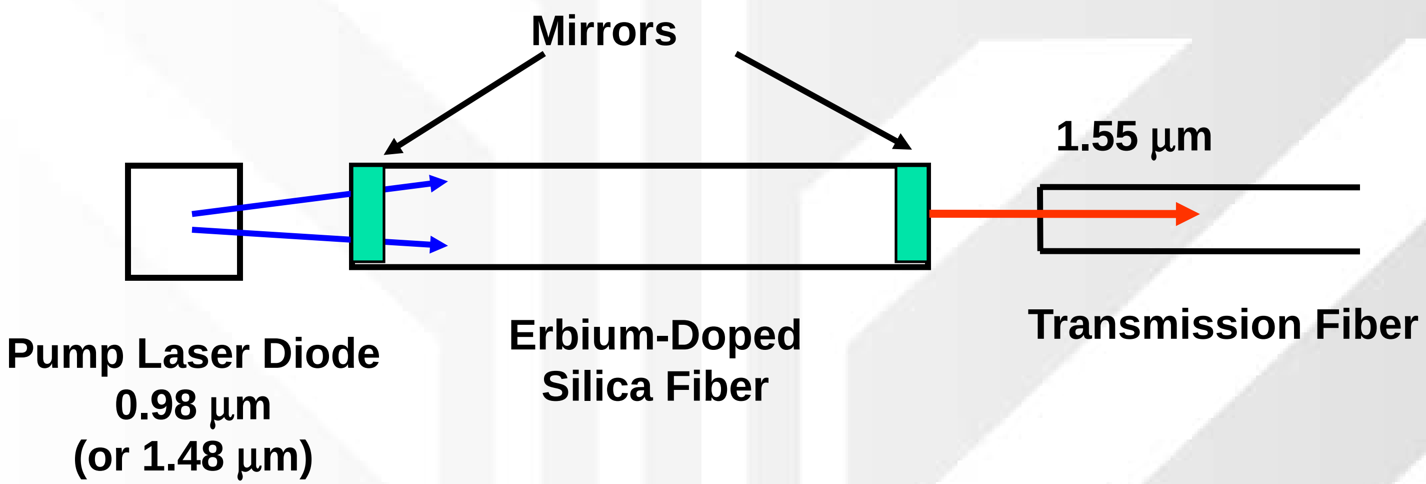
in dB à

$$F_{dB} = 10\log_{10} F = (S/N)_{in,dB} - (S/N)_{out,dB}$$

Fiber lasers

- Laser diodes and LEDs couple inefficiently into glass fibers.
- If we can build a laser in the form of a fiber, coupling would be much better.
- We know that fiber amplifiers are possible, thus a fiber oscillator (i.e., a laser) should be possible.
- Two fiber lasers will be shown in the next slides
  - Fabry-Perot Fiber Laser
  - Erbium Doped Fiber Laser

Fabry-Perot Fiber Laser

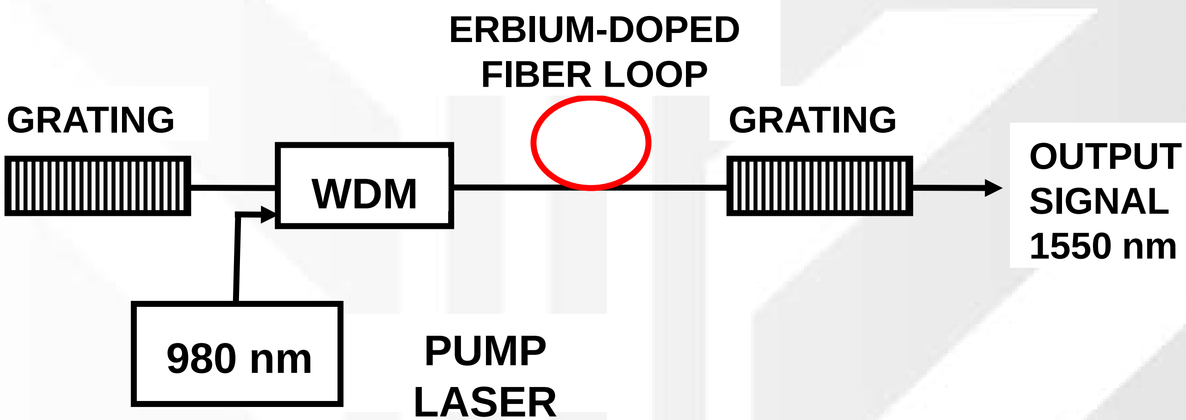


- The first mirror is designed such that it is highly reflective for wavelength 1.55μm

  and highly Transmissive for wavelength 0.98μm

- The second mirror is partially transmissive at λ=1.55μm

Erbium doped fiber laser



GRATING: Fiber Bragg grating

WDM: Wavelength division multiplexer

- The fiber Bragg gratings act as reflectors.
- The wavelength division multiplexer (WDM) couples the pump light into the erbium-doped fiber loop.

External Modulators

Optical Modulation

- Direct modulation on semiconductor lasers:
  - Output frequency shifts with drive signal
    - carrier induced (chirp)
    - temperature variation due to carrier modulation
  - Limited extinction ratio à because we don't want to turn off laser at 0-bits
  - Impact on distance*bit-rate product
- External modulation
  - Electro-optical modulation
  - Electroabsorption (EA) modulation
    - Chirp can still exist
    - Facilitates integration
  - Always incur 6-7 dB insertion loss

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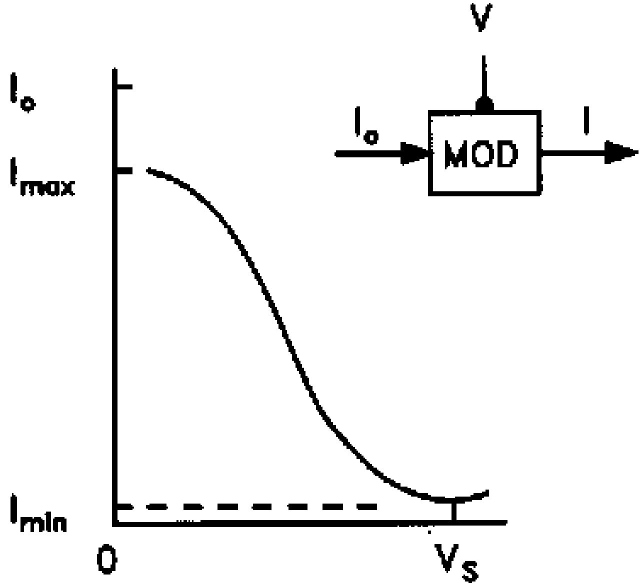
- *Desirable Properties*
  - High electrooptic coefficients
  - High optical transparency near telecom transmission λ
  - High T_C
  - Mechanically and chemically stable
  - Manufacturing compatibility

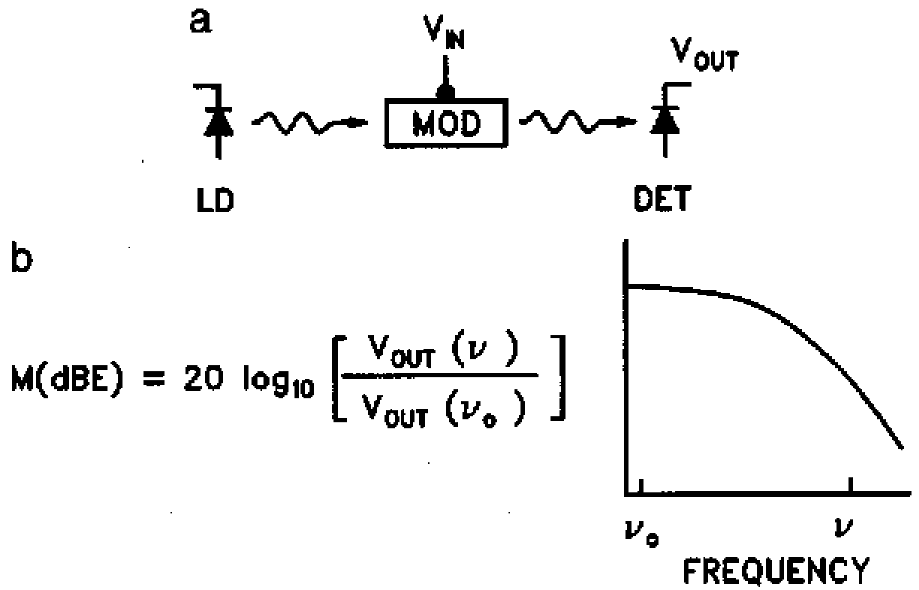
Table 1.10. Physico-chemical constants of $LiNbO_3$ crystals (according to Kuz'minov 1975).

Characteristic	Experimental data
Density of single crystals ($g\,cm^{-3}$)	4.612
Mohs' hardness	5
Melting point (°C)	1260
Curie point (°C)	1210
Parameters of a unit cell:	
Rhombohedral	
a (Å)	5.4920
Angle	55°53′
Hexagonal	
a (Å)	5.148 29 ± 0.000 02
c (Å)	13.863 10 ± 0.000 04
Number of formula units in cells	
Rhombohedral	2
Hexagonal	6
Thermal expansion coefficient	
a axis	16.7 ± 10^{-6}
c axis	2.0 ± 10^{-6}
Dielectric constant	$\varepsilon^s_{11} = 44$ $\varepsilon^t_{11} = 84$
	$\varepsilon^s_{33} = 29$ $\varepsilon^t_{33} = 30$
	$\varepsilon^s_{11} = 43$ $\varepsilon^t_{11} = 78$
	$\varepsilon^s_{33} = 49$ $\varepsilon^t_{33} = 32$
Refractive indices ($\lambda = 0.623\ \mu m$)	$n_o = 2.286$ $n_e = 2.22$[illegible]

switching curve



modulation response



Insertion loss (dB) = 10 $\log_{10}(I_{max}/I_0)$

Extinction ratio (dB) = -10 $\log_{10}(I_{min}/I_{max})$

Typical Electrooptic Modulator

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Electrooptic effect

$$\Delta\varepsilon_{ij} = \begin{bmatrix} -r_{22}E_y^a + r_{13}E_z^a & -r_{22}E_x^a & r_{51}E_x^a \\ -r_{22}E_x^a & r_{22}E_y^a + r_{13}E_z^a & r_{51}E_y^a \\ r_{51}E_x^a & r_{51}E_y^a & r_{33}E_z^a \end{bmatrix}$$

Optical phase shift = $\Delta\Phi = \Delta\beta_O L = k_O \Delta n_{eo} L$

Local change in index of refraction = $\Delta n_{eo} = -(n^3 r/2)E^a$

Effective change of index = $\Delta N_{eo} = -(n^3 r/2)\Gamma(V/G)$

$$\Delta n = \frac{-n^3 r}{2}\,\frac{V}{G}\,\Gamma$$

eg.

$n \sim 2.2$

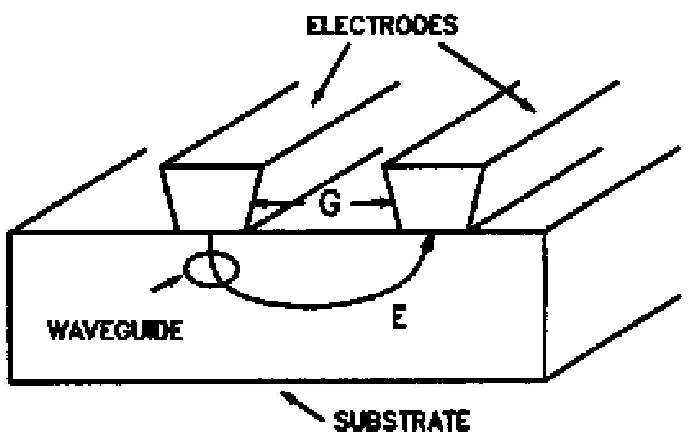
$\lambda \sim 1.5\ \mu m$

$G \sim 15\ \mu m$

$r \sim 30\ pm/V$

$\Gamma \sim 0.5$

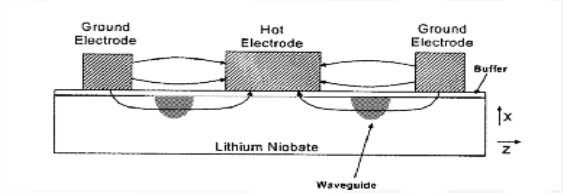
$\Delta n \sim 2 \times 10^{-5}$

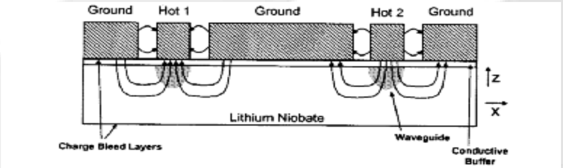


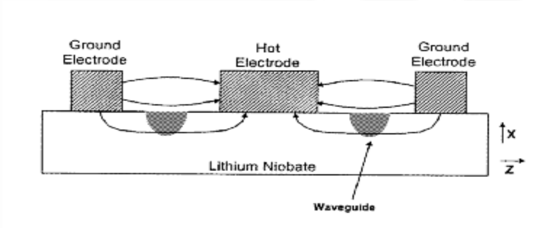
$$V_\pi \times L = \frac{\lambda\, G}{n^3\ r\ \Gamma}$$

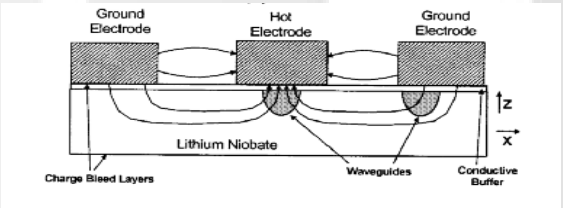
Device design

Most common electrode configurations (MZI)

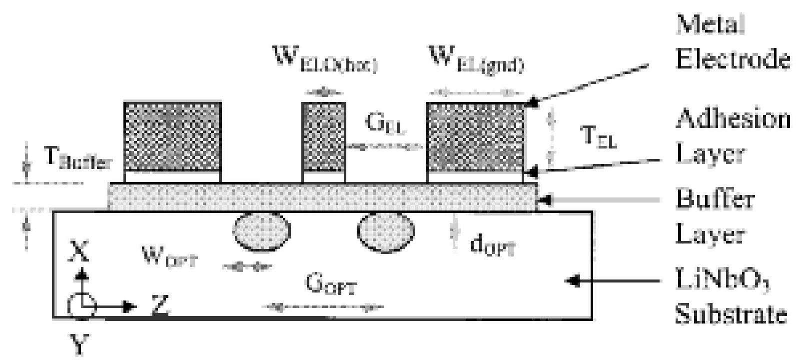




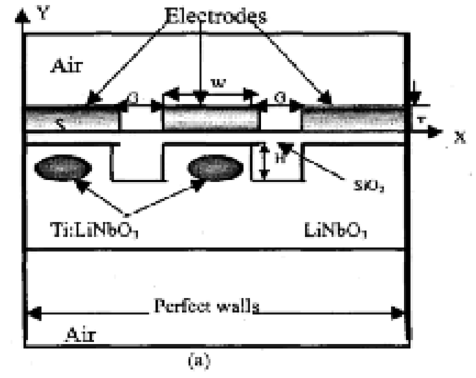




Fabrication



Cross section of x-cut coplanar-waveguide



Cross section of z-cut ridge-waveguide

- Waveguides
  - Ti diffusion
    - ~1000 oC.
    - Li out-diffusion must be minimized.
  - Annealed proton exchange (APE)
    - Acid bath
    - ~125-250 oC.
- *Electrodes*
  - Electroplated.
  - Typically Au.
  - Deposited directly on $LiNbO_3$ or on optically transparent buffer layer.
  - ~3-15 μm thick.

Fabrication

- *Dicing & Polishing*
  - $LiNbO_3$ crystals do not cleave like GaAs or InP
    - Diamond saw cutting
  - Crystal ends cut at an angle to waveguide to reduce reflections.
  - Both ends are polished to an optical finish.
  - Must be free from debris and polishing compounds.

Fabrication

- *Pigtailing & Packaging*
  - subassemblies
    - Integrated-optic chip
      - The “waveguide”
    - Optical-fiber assemblies
      - Input (polarization maintained) and output (single-mode) fibers
    - Electrical or RF interconnects and housing
      - Package to modulator housing.

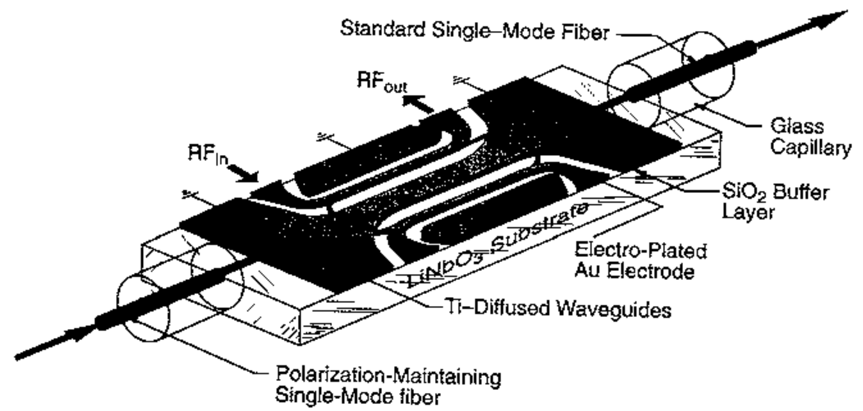
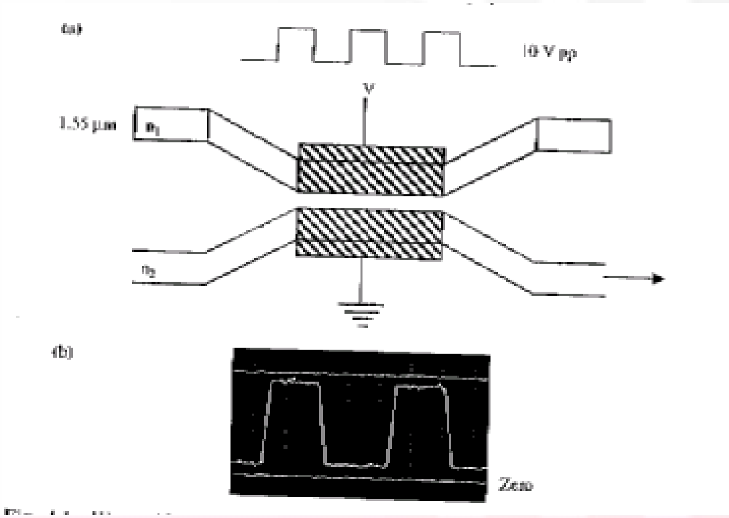


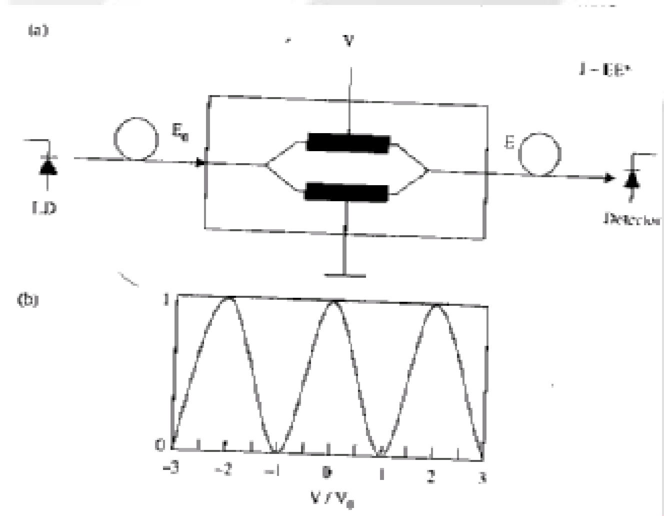
Fig. 9.11 Schematic of a dual-drive Ti : $LiNbO_3$ Y-branch Mach–Zehnder modulator.

Modulator Design

- Directional Coupler:
  - Use reversed β-coupler
  - Requires small waveguide separation for coupling
  - Difficult to design for high frequency à low speed modulators



- Mach-Zehnder Interferometer
  - BW as high as 75 GHz (Noguchi, 1994)
  - Use electro-optic effect to vary index
  - leverage interference effect



Device design

Most popular designs

Mach-Zehnder Interferometer

•Light is split into two *isolated (non-interacting)* waveguides.

•Applied electric field from electrode modifies relative velocities via the *electrooptic effect*

•Hence, a variable interference when light combined at output

Directional Coupler

•Light is split into two or more *coupled (interacting)* modes of a waveguide structure.

•Applied electric field from electrode modifies relative velocities *and* coupling between waveguide modes.

Device design

Advantages

Mach-Zehnder Interferometer

•Accommodates large electrode design needed for hi bandwidth applications.

•Higher modulation speed for a given voltage.

•Higher extinction ratio at higher speed.

Directional Coupler

•Small size and compact

Modulator Design

- Traveling wave electro-optic modulator

- It is necessary to match RF propagation with optical propagation
- Combine with MZI design
- 2-4 cm long and <6V drive

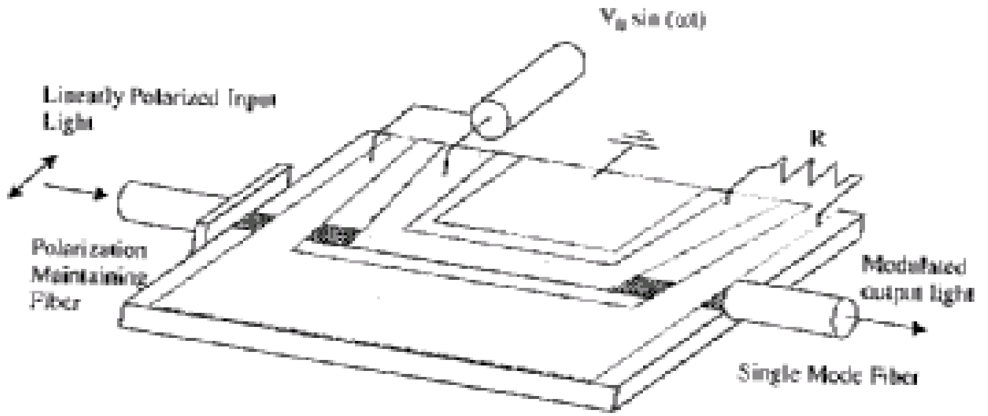


Fig. 4.3 Schematic diagram of a traveling-wave electrooptic modulator.

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System Requirements

- typical NRZ transmitter

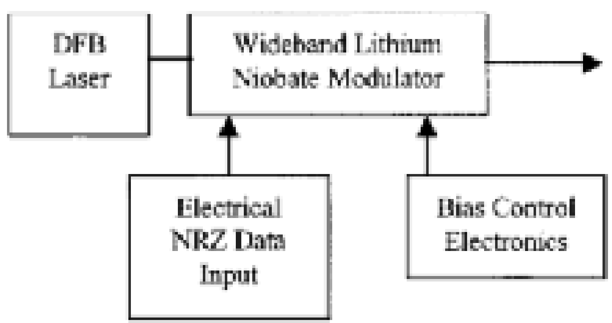


Fig. 6. Data modulator topology for NRZ transmission.

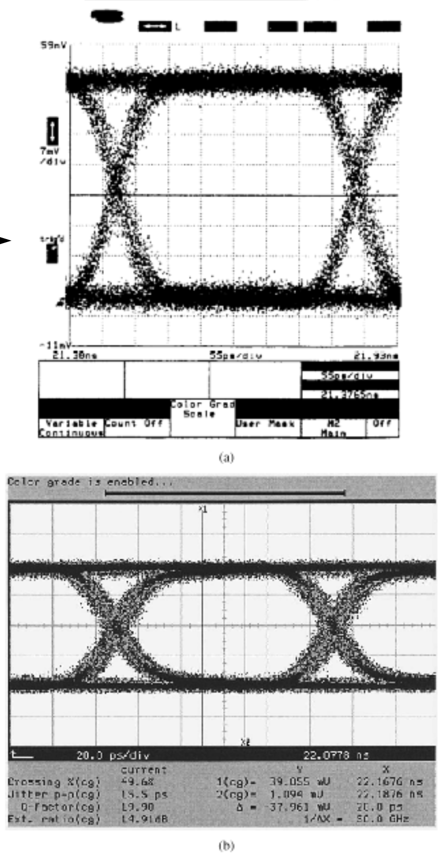


Fig. 7. $LiNbO_3$ externally modulated eyes at (a) 2.5 and (b) 10 Gb/s.

System Requirements

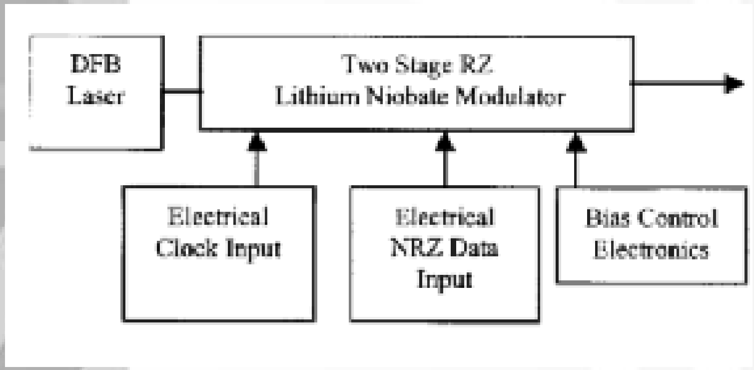
- DWDM demands various data encoding formats and modulation techniques

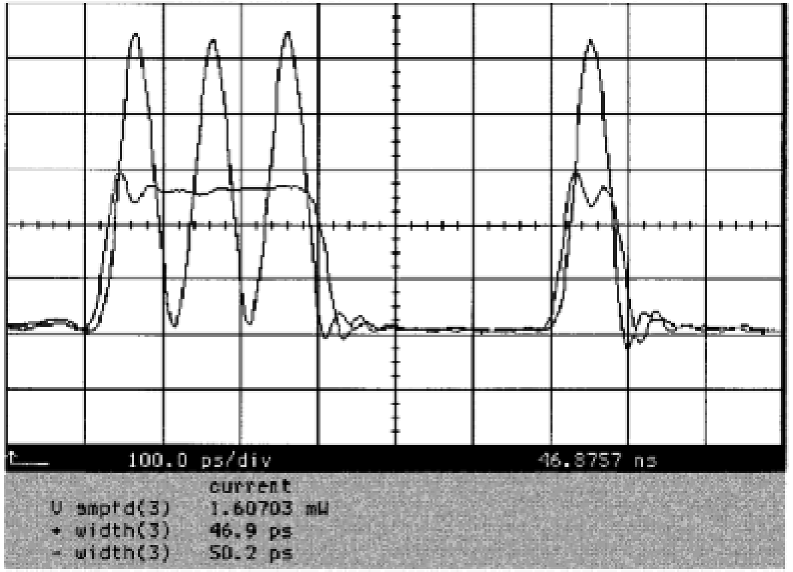
TABLE II
MODULATION FORMATS

Modulation Technique	Optical spectra	Data format	Comments
AM – NRZ (Amplitude Modulated – Non-Return –to-Zero)	Double sideband, with carrier	NRZ (typical)	Bandwidths typically twice the information bandwidth (or more), significant carrier power.
AM - RZ (Amplitude Modulated – Return-to-Zero)	Double sideband, with carrier	RZ	Bandwidths typically 4 times the information bandwidth (or more), significant carrier power
SSB (Single Sideband)	Single sideband	NRZ	Bandwidths ½ AM bandwidths Increased dispersion tolerance
DSSC (Double-Sideband Suppressed Carrier)	Double sideband suppressed carrier	Duo-Binary	Requires special modulation techniques, external modulator typically used
PM (Phase Modulated)	Phase modulation	PM	Used for linewidth broadening and dispersion compensation.

Performance

§ typical RZ transmitter





Reliability

- Quite reliable!
  - Failure rate assumptions
    - random
    - exponentially distributed
    - failures in time per 109 device hours (FIT)

TABLE III
FIELD FAILURE RATES FOR $LiNbO_3$ MODULATORS

FIELD DATA	2.5 Gb/s, X-Cut, Ti Waveguide	2.5 Gb/s, X-Cut, APE Waveguide
In-service device hours	> 100,000,000	> 300,000,000
FIT rate at 60% confidence	9	10
FIT rate at 95% confidence	30	21

- Bias voltage drift

  è *not a failure mechanism*

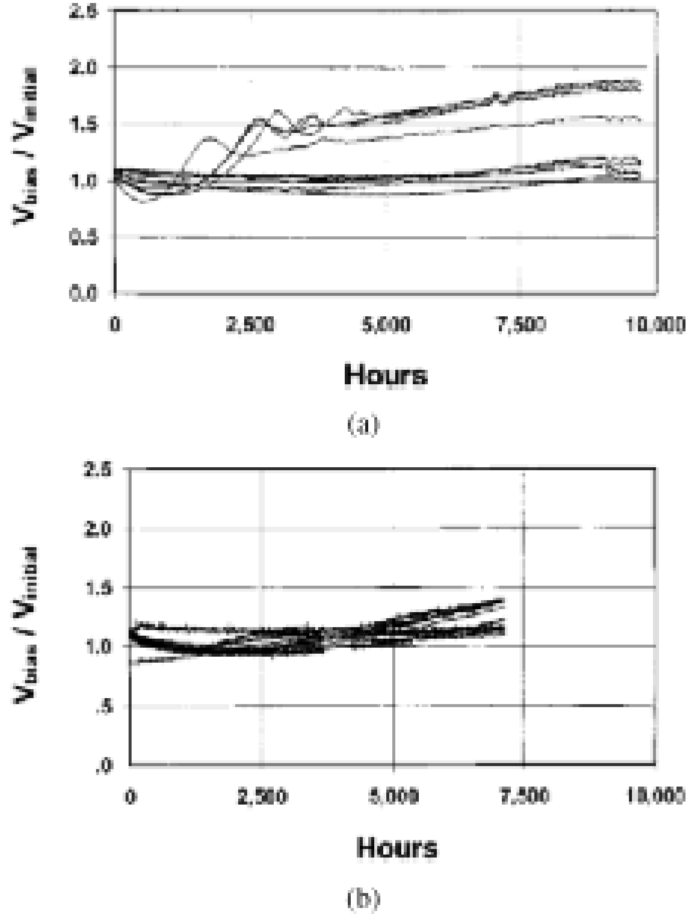


Fig. 11. Bias voltage drift for 2.5 Gb/s, x-cut, Ti modulators at (a) 85 and (b) 100 ℃ [19].

Reliability

- Insertion loss
  - minimal losses for 10,000 hours of operation
    - good fiber to modulator interface
    - robust optical circuit

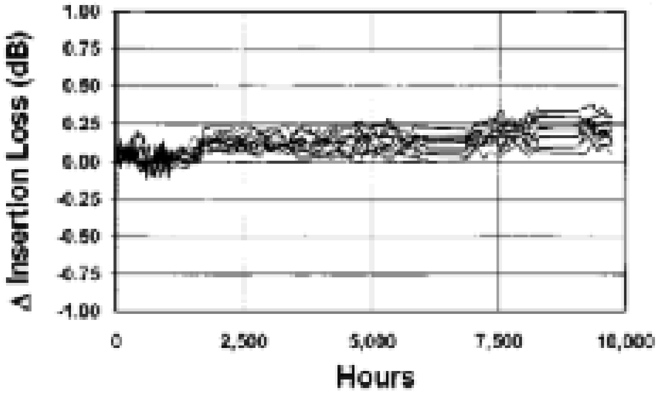


Fig. 15. Change in insertion loss with time, 85 °C, 2.5 Gb/s, x-cut, Ti modulators [19].

Optical Fiber

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Optical Fiber

- Propagation of light in atmosphere impractical: water vapor, oxygen, particles.
- Optical fiber is used, glass or plastic, to contain and guide light waves
- Capacity
  - **Microwave at 10 GHz with 10% utilization ratio: 1 GHz BW**
  - **Light at 100 Tera Hz (10^{14}) with 10% utilization ratio: 100 THz (10,000GHz)**

History

- 1880 Alexander G. Bell, Photo phone, transmit sound waves over beam of light
- 1930: TV image through uncoated fiber cables.
- Few years later image through a single glass fiber
- 1951: Flexible fiberscope: Medical applications
- 1956:The term “fiber optics” used for the first time
- 1958: Paper on Laser & Maser

History

- 1960: Laser invented
- 1967: New Communications medium: cladded fiber
- 1960s: Extremely lossy fiber: more than 1000 dB /km
- 1970: Corning Glass Work NY, Fiber with loss of less than 2 dB/km
- 70s & 80s : High quality sources and detectors
- Late 80s : Loss as low as 0.16 dB/km

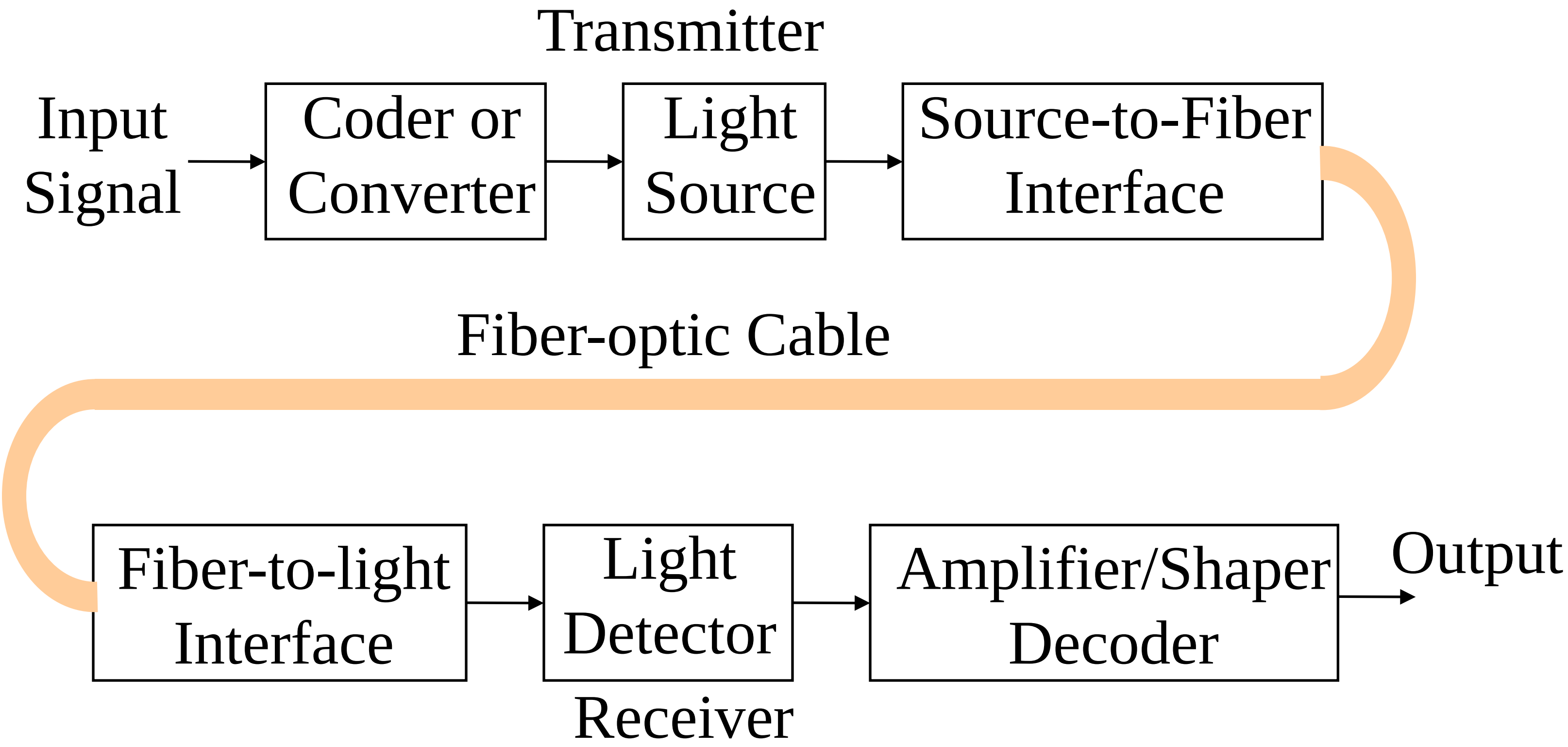
Optical Fiber: Advantages

- Capacity: much wider bandwidth (10 GHz)
- Crosstalk immunity
- Immunity to static interference
- Safety: Fiber is nonmetalic
- Longer lasting (unproven)
- Security: tapping is difficult
- Economics: Fewer repeaters

Disadvantages

- higher initial cost in installation
- Interfacing cost
- Strength: Lower tensile strength
- Remote electric power
- more expensive to repair/maintain
  - Tools: Specialized and sophisticated

Optical Fiber Link



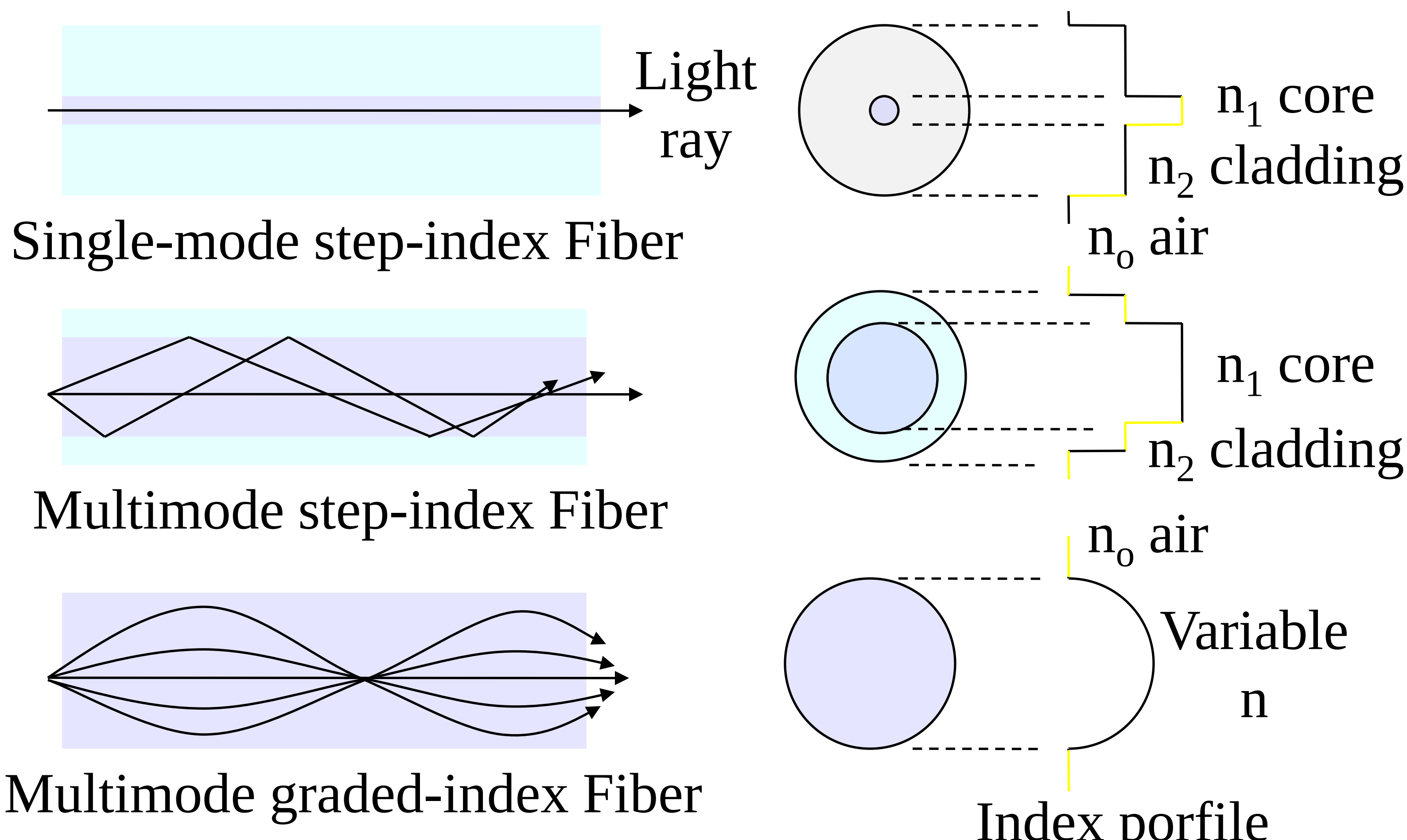
Fiber Types

- Plastic core and cladding
- Glass core with plastic cladding PCS (Plastic-Clad Silicon)
- Glass core and glass cladding SCS: Silica-clad silica
- Under research: non silicate: Zinc-chloride:
  - **1000 time as efficient as glass**

Plastic Fiber

- used for short run
- Higher attenuation, but easy to install
- Better withstand stress
- Less expensive
- 60% less weight

Types Of Optical Fiber



Single-mode step-index Fiber (Standard Single Mode Fiber)

Advantages:

- Minimum dispersion: all rays take same path, same time to travel down the cable. A pulse can be reproduced at the receiver very accurately.
- Less attenuation, can run over longer distance without repeaters.
- Larger bandwidth and higher information rate

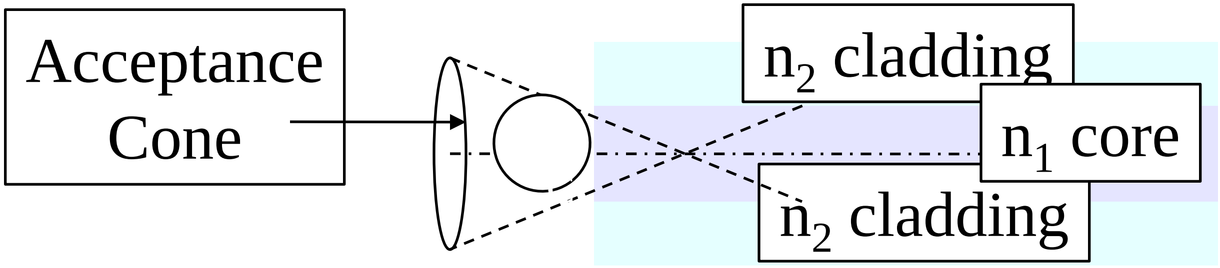
Disadvantages:

- Difficult to couple light in and out of the tiny core
- Highly directive light source (laser) is required.
- Interfacing modules are more expensive

Multi Mode

- Multimode step-index Fibers:
  - inexpensive; easy to couple light into Fiber
  - result in higher signal distortion; lower TX rate
- Multimode graded-index Fiber:
  - intermediate between the other two types of Fibers

Acceptance Cone & Numerical Aperture



Acceptance angle, θ_c, is the maximum angle in which external light rays may strike the air/Fiber interface and still propagate down the Fiber with <10 dB loss.

$$\theta_C = \sin^{-1}\sqrt{n_1^{\,2} - n_2^{\,2}}$$

Numerical aperture:
$NA = \sin\theta_c = \sqrt{(n_1^2 - n_2^2)}$

Losses In Optical Fiber Cables

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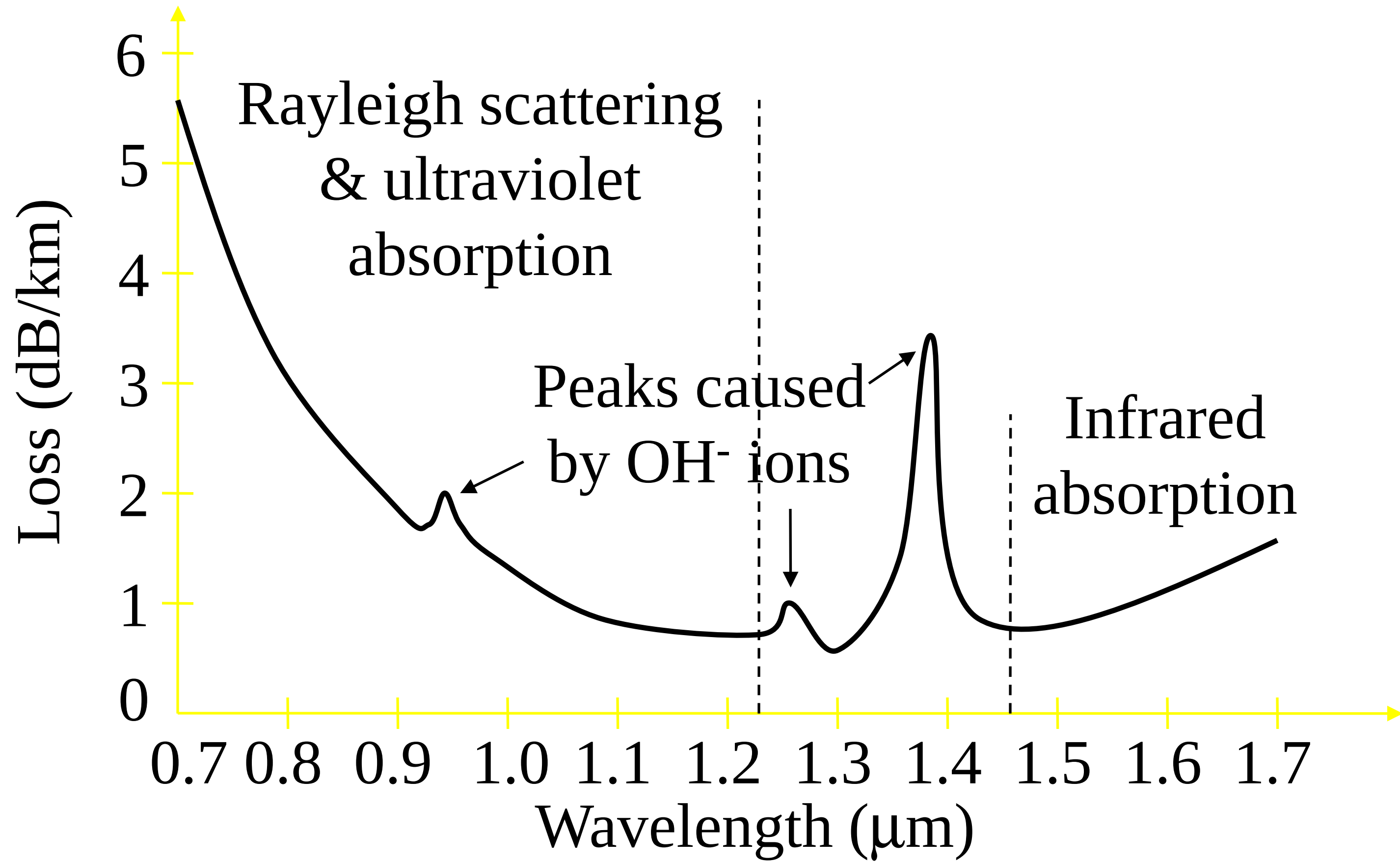
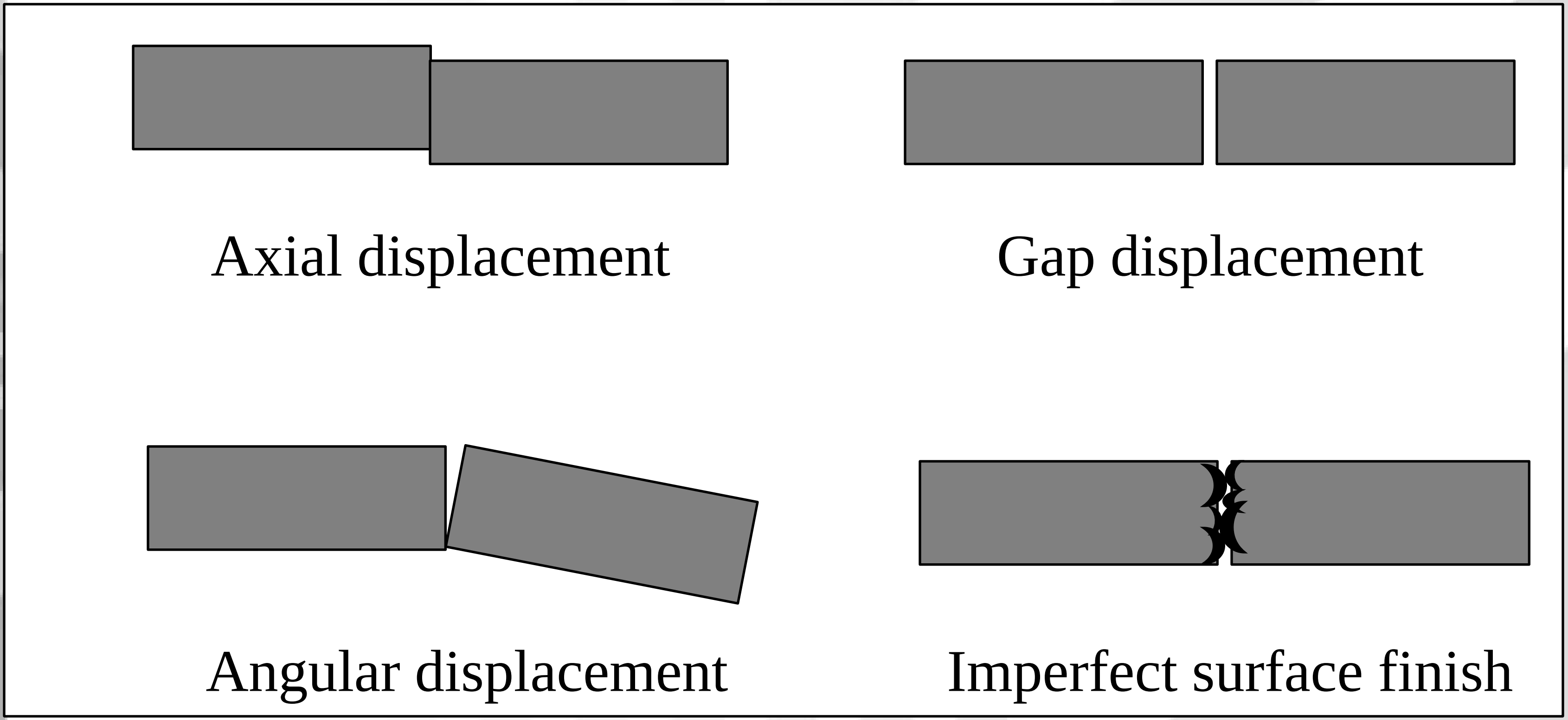
- The predominant losses in optic Fibers are:
  - **absorption losses due to impurities in the Fiber material**
  - **material or Rayleigh scattering losses due to microscopic irregularities in the Fiber**
  - **chromatic or wavelength dispersion because of the use of a non-monochromatic source**
  - **radiation losses caused by bends and kinks in the Fiber**
  - **modal dispersion or pulse spreading due to rays taking different paths down the Fiber**
  - **coupling losses caused by misalignment & imperfect surface finishes**

Absorption Losses In Optic Fiber



Fiber Alignment Impairments



Light Sources

- Light-Emitting Diodes (LED)
  - made from material such as AlGaAs or GaAsP
  - light is emitted when electrons and holes recombine
  - either surface emitting or edge emitting
- Injection Laser Diodes (ILD)
  - similar in construction as LED except ends are highly polished to reflect photons back & forth

ILD versus LED

Advantages:

- more focussed radiation pattern; smaller Fiber
- much higher radiant power; longer span
- faster ON, OFF time; higher bit rates possible
- monochromatic light; reduces dispersion

Disadvantages:

- much more expensive
- higher temperature; shorter lifespan

Light Detectors

PIN Diodes

- photons are absorbed in the intrinsic layer
- sufficient energy is added to generate carriers in the depletion layer for current to flow through the device

Avalanche Photodiodes (APD)

- photogenerated electrons are accelerated by relatively large reverse voltage and collide with other atoms to produce more free electrons
- avalanche multiplication effect makes APD more sensitive but also more noisy than PIN diodes

That's it!!!!

Photodiodes

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Light Detectors

- The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the light wave system
- Its main component is a photodetector that converts light into electricity through the photoelectric effect

Principles of Photo detection

- **External Photoelectric Effect**
  - – Electrons are freed from the surface of a metal by the energy absorbed from an incident stream of photons. e.g. vacuum photodiode and photomultiplier are based on this effect
- **Internal Photoelectric Effect**
  - – In semiconductor junction devices, free charge carriers are generated by absorption of incoming electrons e.g. pn junction photodiode, PIN photodiode and the avalanche photodiode are based on this

Vacuum Photodiode

- When the cathode is irradiated with light, incoming photons are absorbed, giving up their energies to electrons in the metal.
- Some of these electrons gain enough energy to escape from the cathode. These free electrons move toward the anode, attracted by its positive charge.
- During this movement, positive charge is drawn through the external circuit causing a current to flow.

Detector Properties

- **Responsivity**

$$\rho = i / P$$

The responsivity is the ratio of the output current of the detector to its optic input power.

- **Spectral Response**

It refers to the curve of detector responsivity as a function of wavelength. The responsivity at the specific wavelength emitted by the source must be used when designing the receiver.

Detector Properties

- **Quantum Efficiency**
  - Not every photon whose energy is greater than the work fn will liberate an electron. This characteristic is described by quantum efficiency

$$\eta = \frac{\text{No. of emitted electrons}}{\text{No. of incident photons}}$$

Detector Properties

- Since, each electron carries charge of magnitude e, the charge per second emerging from cathode is

$$i = \eta eP/hf = \eta e\lambda P/hc$$

- The responsivity is now

$$\rho = i\ /\ P = \eta e/hf = \eta e\lambda/hc \ \text{(A/W)}$$

Optic power is the energy per second being delivered to the detector
hf is the energy per photon
P/hf is the No. of photons/sec
η is the Quantum efficiency
Number of emitted electrons /sec is *then* ***ηP/hf***

– Compute the responsivity of a detector having a quantum efficiency of 1% at 0.8um

Solution:

As $\rho = \eta e\lambda/hc$

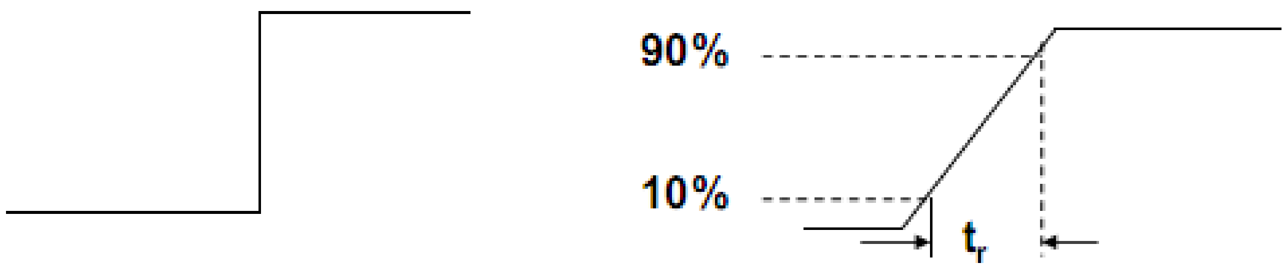
$$= \frac{0.01(1.6\text{x}10^{-19})(0.8\text{x}10^{-6})}{(6.63\text{x}10^{-34})(3\text{x}10^{8})}$$

$= 0.0064$ A/W

Detector Properties

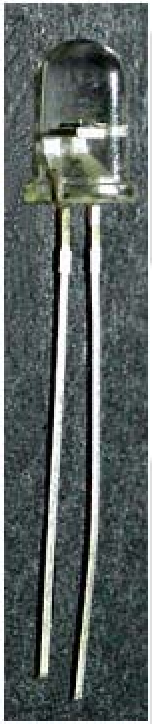
- **Rise Time:**

  Rise Time t_r is the time for the detector output current to change from 10 to 90% of its final value when the optic input power variation is a step.



Semiconductor PD

- Photodetectors made up of S.C materials
- Photons incident on S.C absorbed by electrons in valence band
- These electrons acquire higher energy and are excited into the conduction band, leaving behind a hole in the valence band.
- When an external voltage is applied to the semiconductor, these electron-hole pairs give rise to an electrical current, termed as photocurrent.
- Principle of quantum mechanics is that each electron can absorb only one photon to transit between energy levels



PD principles

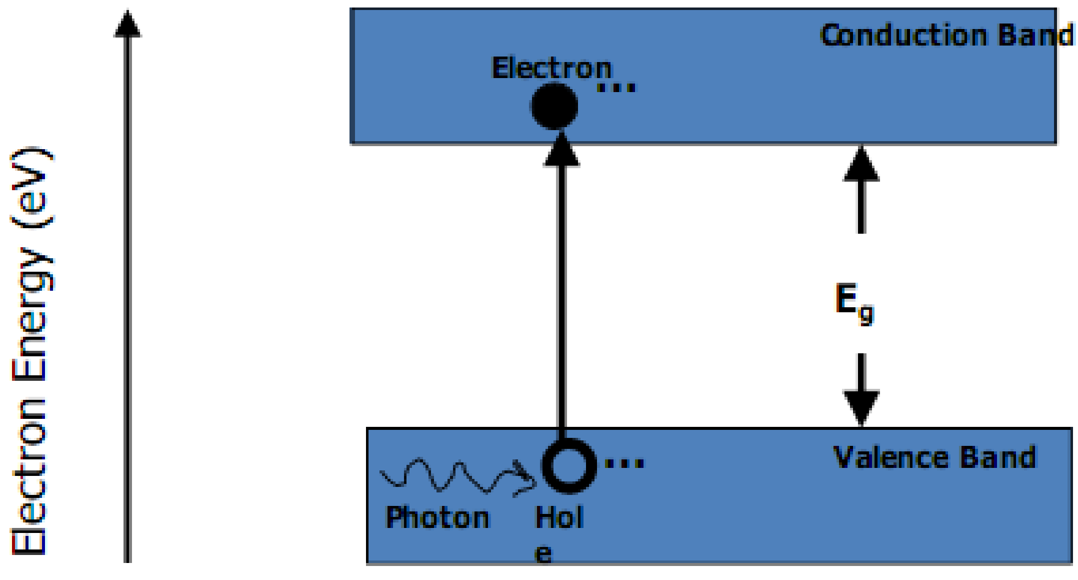


Fig: 3.62
The basic principle of photodetection using a semiconductor. Incident photons are absorbed by electrons in the valence band, creating a free or mobile electron-hole pair.
Electron-hole pair gives rise to a photocurrent when an external voltage is applied.

PD Materials

Material	Wavelength range (nm)
Silicon	190–1100
Germanium	800–1700
Indium gallium arsenide	800–2600
lead sulfide	<1000-3500

PD principles

- Energy of the incident photon must be at least equal to the band gap energy in order for a photocurrent to be generated.

- This gives us the following constraint on the frequency f_c or the wavelength λ at which a semiconductor material with band gap E_g can be used as a photodetector

$$hf_c = hc/\lambda \geq eE_g$$

- The Largest value of λ for which this equation is satisfied is called the cutoff wavelength and is denoted by λ_{cutoff}

PD principles

- The power absorbed by a semiconductor slab of thickness L μm can be written as

$$P_{abs} = (1- e^{-\acute{\alpha}L})\ P_{in}$$

- Where P_{in} is the incident optical signal power, and α is the absorption coefficient of the material.

- ά depends on the wavelength and is zero for wavelengths $\lambda > \lambda_{cutoff}$

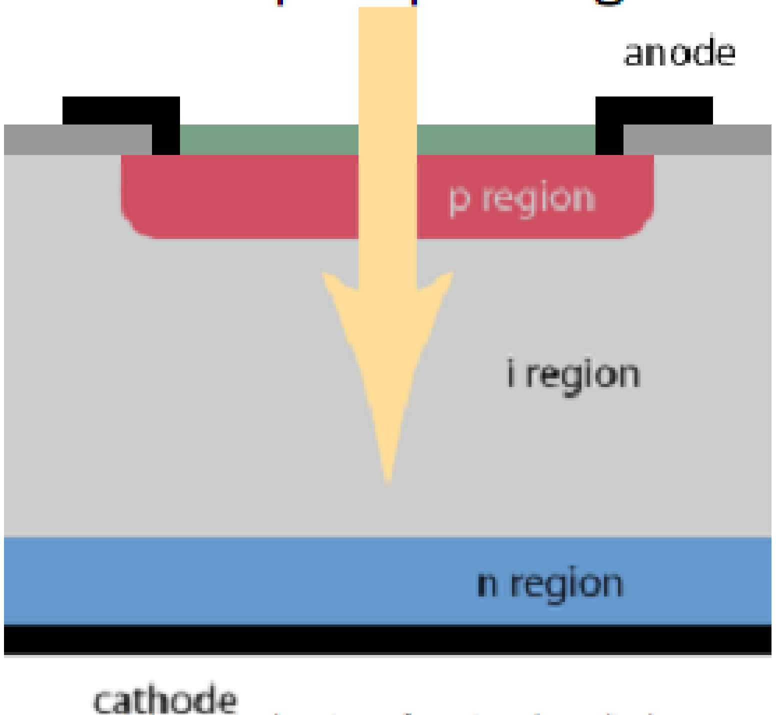
PD principles

- Area of the photodetector is usually chosen to be sufficently large so that all the incident optical power can be captured by it
- Photodectectors have very wide operating bandwidth since a photodetector at some wavelength can also serve as a photodetector at all smaller wavelengths
- Thus a photodetector designed for the 1.55µm band can also be used in the 1.3µm

Material	E_g (eV)	λ_{cutoff} (μm)
Si	1.17	1.06
Ge	0.775	1.6
GaAs	1.424	0.87
InP	1.35	0.92
$In_{0.55}Ga_{0.45}As$	0.75	1.65
$In_{1-0.45y}Ga_{0.45y}As_yP_{1-y}$	0.75-1.35	1.65-0.92

PIN Photodiode

- A p-i-n photodiode, also called *PIN photodiode*, is a photodiode with an intrinsic (i) (i.e., undoped) region in between the n- and p-doped regions



Schematic drawing of a p-i-n photodiode

PIN Photodiode

- As the intrinsic layer is so wide, there is a high probability that incoming photons will be absorbed in it rather than in the thin p or n regions.
- This improves the efficiency and the speed relative to the *pn* photodiode

PIN Photodiode

- Compared with an ordinary p-n photodiode, a p-i-n photodiode has a thicker depletion region, which allows a more efficient collection of the carriers and thus a larger quantum efficiency

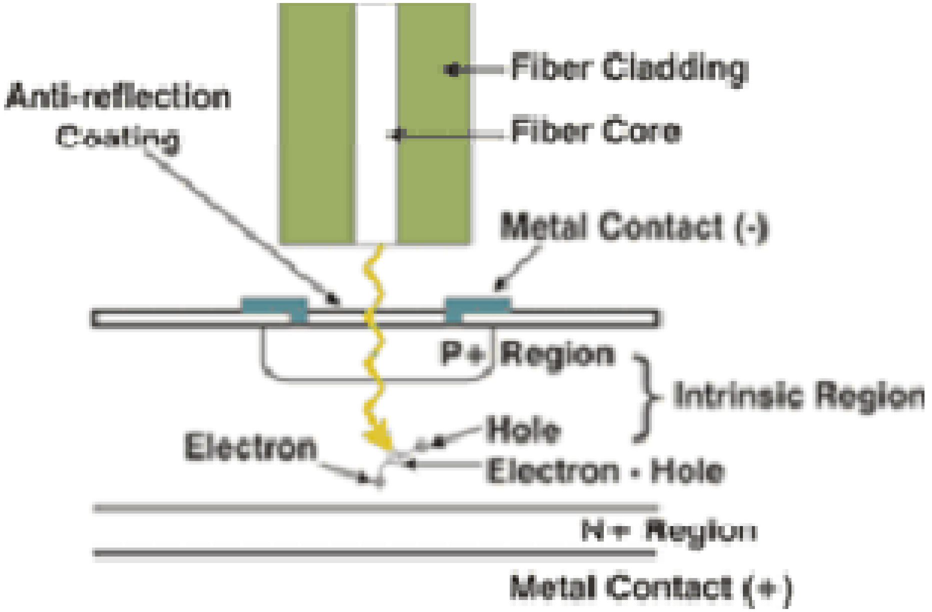
- This leads to a lower capacitance and thus to higher detection bandwidth

PIN Photodiode

- Most common PIN photodiodes are based on silicon
- Sensitive throughout the visible region and near infrared region up to roughly 1 µm
- Absorption efficiency drops at longer wavelengths
- InGaAs pin photodiodes are available for longer wavelengths i.e., 1.7 µm, but they are expensive

PIN Photodiode

- Germanium pin diodes can be an alternative



– Compute the cut-off wavelength for Silicon and Germanium PIN diodes. Their bandgap energies are 1.1 eV and 0.67 eV respectively.

- Solution:

Using $\lambda=1.24/ W_g$

Cutoff wavelength for Silicon = 1.1um

Cutoff wavelength for Germanium = 1.85 um

Avalanche Photodiode

- The APD is a semiconductor junction detector that has internal gain, which increases its responsivity
- It operates on a relatively high reverse voltage
- Carriers (electrons & holes) excited by absorbed photons are strongly accelerated in the strong internal electric field
- This effect creates secondary carries, as it occurs in photo-multipliers

Avalanche Photodiode

- This process increases the photocurrent by a significant factor
- However, avalanche process itself is subject to amplification noise that can reduce said advantage
- Noise performance is better than pin photodiodes

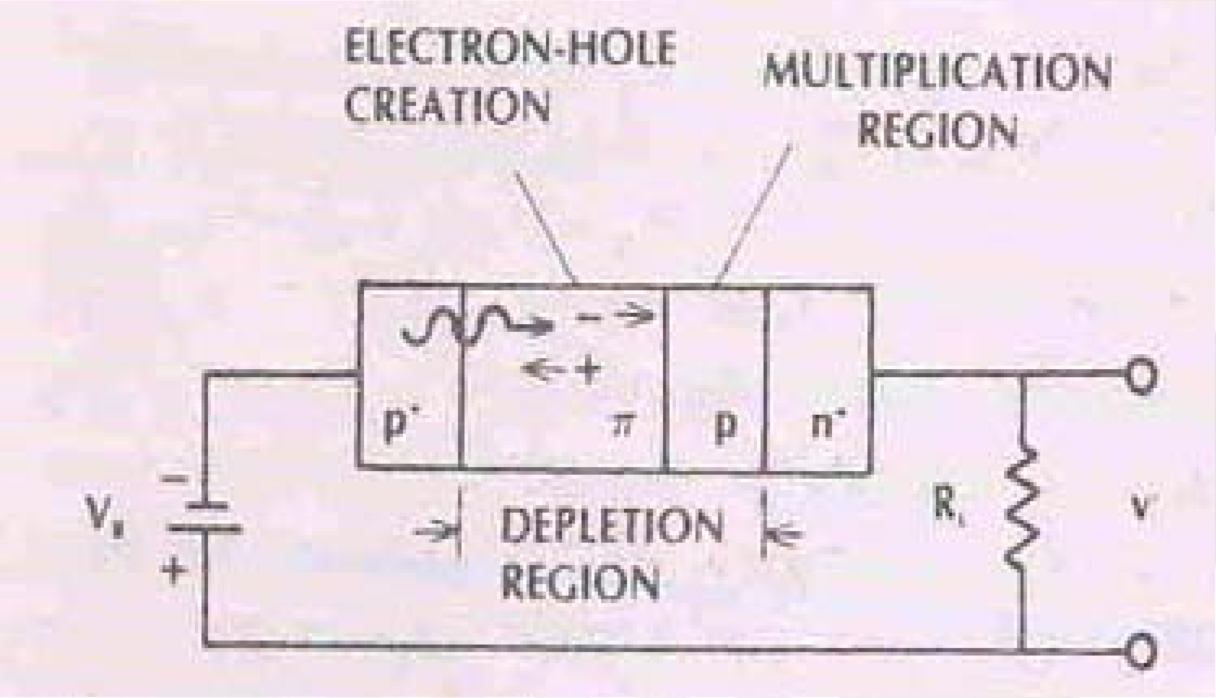
Avalanche Photodiode

- APDs internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier
- Increases receiver sensitivity
- In order for carrier multiplication to take place, the photo-generated carriers must traverse a region where a very high electric field is present

Avalanche Photodiode

- Silicon-based avalanche photodiodes are sensitive in the wavelength region of ≈450-1000 nm
- Maximum responsivity occurs around 600-800 nm
- For longer wavelengths, APDs based on Ge or InGaAs are used

Avalanche Photodiode



- Under reverse bias, a high electric field exists in the p-type layer sandwiched between the i-type and n type layers, this layer is referred to as the multiplication layer

Avalanche Photodiode

- In this high-field region, a photo-generated electron or hole can gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them

- This mechanism is called Impact Ionization

Avalanche Photodiode

- Avalanche Current Multiplication:
  - A photon is absorbed in the depletion region, creating a free electron and a free hole.
  - The large electrical forces cause these charges to accelerate, gaining kinetic energy
  - When fast charges collide with neutral atoms, they create additional electron-hole pairs by using part of their kinetic energy to raise electrons across the energy bandgap
  - One accelerating charge can generate several secondary charges
  - The secondary charges can themselves accelerate and create even more electron-hole pairs, this is the process of avalanche multiplication

Avalanche Photodiode

- The accelerating forces must be strong to impart high kinetic energies, this is achieved with large reverse biases
- The gain increases with reverse bias v_d according to the approximation

$$M = 1/\,(1 - v_d\,/V_{BR})^n$$

where V_{BR} is the diode's reverse breakdown voltage and n is an empirically determined parameter which is more than unity. Breakdown voltages of 20 to 500V occur.

The current generated by an APD with gain M is

$$I = M\eta eP/hf = M\eta e\lambda P/hc$$

Avalanche Photodiode

Material	Structure	Rise Time (ns)	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Gain
Silicon	PIN	0.5	300–1100	0.5	1	1
Germanium	PIN	0.1	500–1800	0.7	200	1
InGaAs	PIN	0.3	900–1700	0.6	10	1
Silicon	APD	0.5	400–1000	75	15	150
Germanium	APD	1	1000–1600	35	700	50
InGaAs	APD	0.25	1000–1700	12	100	20

Thank You