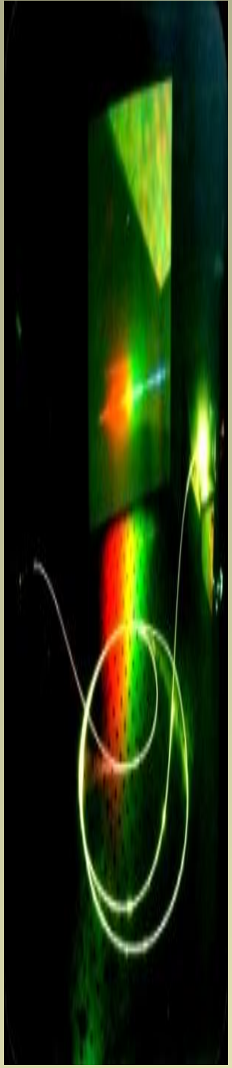
Optical Fibre Communication Systems



Lecture 3: Light Sources

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Contents

- Properties
- Types of Light Source
    - LED
    - Laser
- Types of Laser Diode
- Comparison
- Modulation
- Modulation Bandwidth

Light Sources - Properties

In order for the light sources to function properly and find practical use, the following requirements must be satisfied:

- Output wavelength: *must coincide with the loss minima of the fibre*
- Output power: *must be high, using lowest possible current and less heat*
- High output directionality: *narrow spectral width for coupling to fibre*
- Wide bandwidth
- Low distortion
- Easy to modulate
- Low cost

Light Sources - Types

Every day light sources such as tungsten filament and arc lamps are suitable, but there exists two types of devices, which are widely used in optical fibre communication systems:

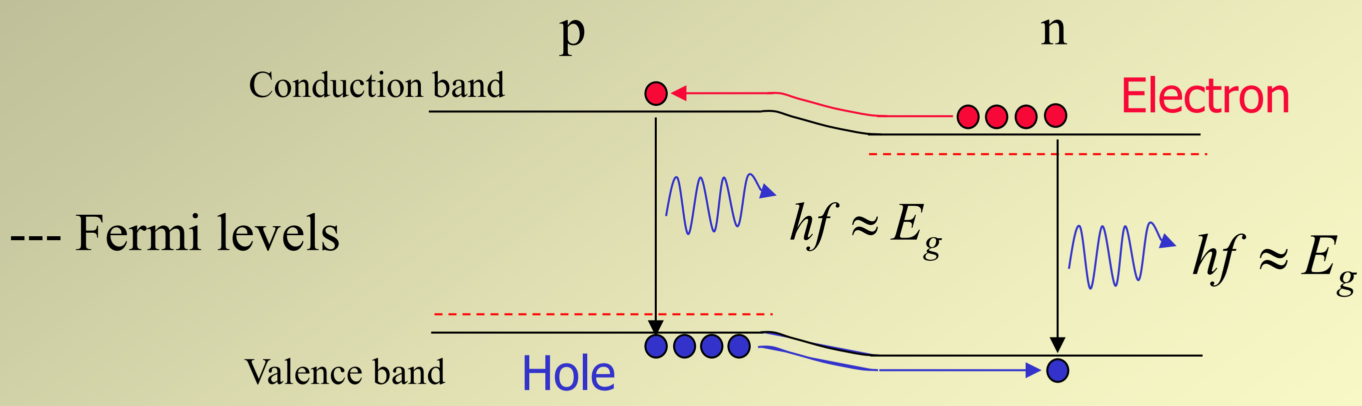
- **Light Emitting Diode (LED)**
- **Semiconductor Laser Diode (SLD or LD).**

In both types of device the light emitting region consists of a **pn junction** constructed of a direct band gap III-V semiconductor, which when forward biased, experiences injected minority carrier recombination, resulting in the generation of photons.

LED - Structure

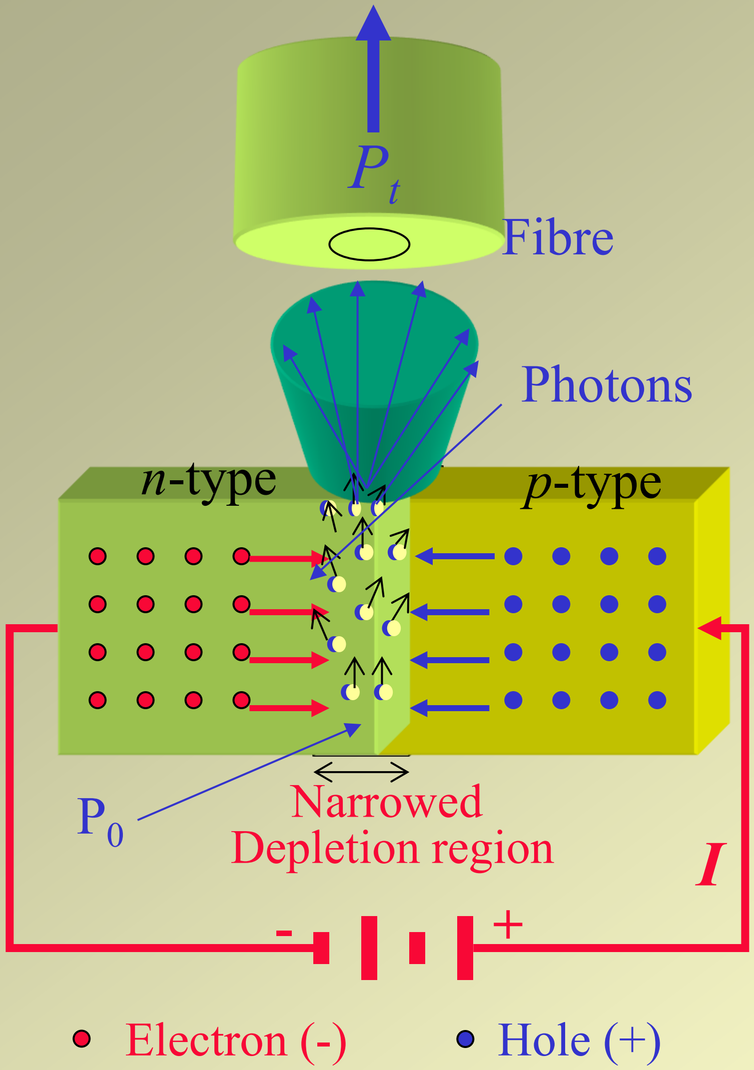
- pn-junction in forward bias

- Injection of minority carriers across the junction gives rise to efficient radiative recombination (**electroluminescence**) of electrons (in CB) with holes (in VB)



Homojunction LED

LED - Structure



- Spontaneous emission
- Radiant intensity: Is a measure for indicating the intensity of light emerging from the LED

$$I_{ra} = \frac{P}{\omega} \qquad \text{W/sr}$$

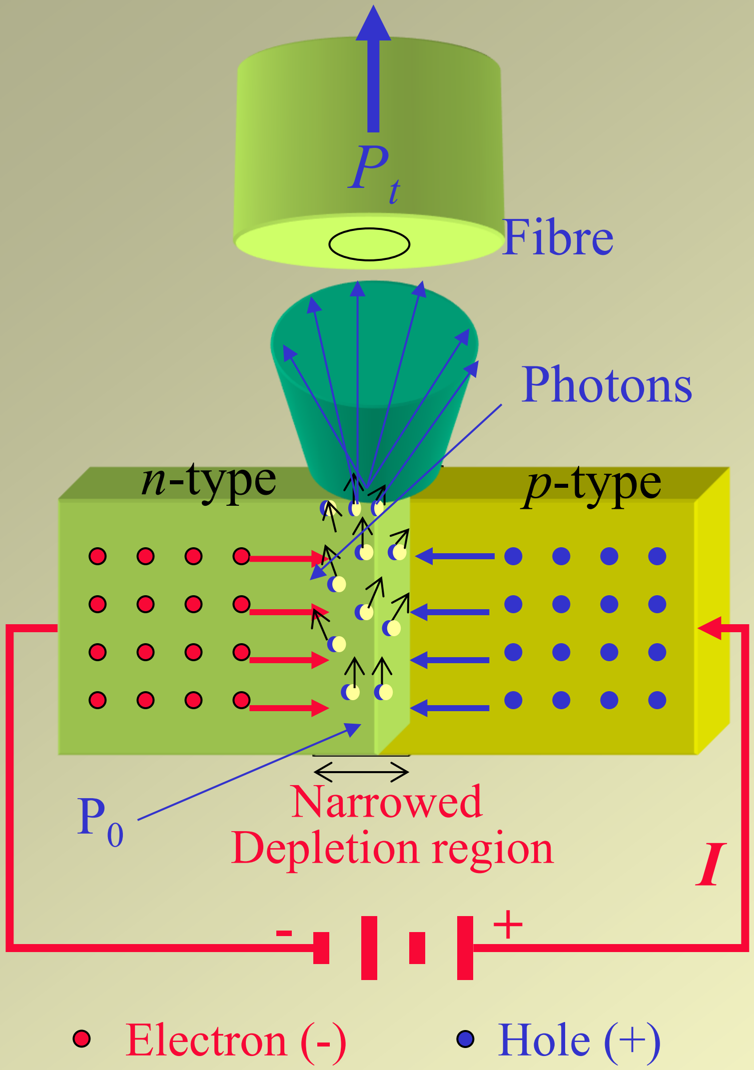
ω is the solid angle = Photodetector Area A_{PD}/ distance from LED to the photodector *d*.
P is the measure light level.

- Irradiance: Is a measure for indicating the intensity of light emerging from the front of an LED

$$E_e = \frac{P}{A_{PD}} \qquad \text{W/cm}^2$$

So inversely proportional to d^2.

LED - Structure



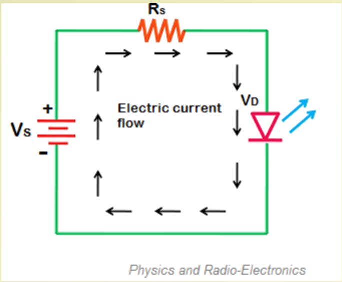
- Spontaneous emission
- Optical power produced by the junction:

$$P_0 = I\frac{\eta_{int}}{q}hf = I\frac{\eta hc}{q\lambda}$$

where

η_{int} = Internal quantum efficiency

q = Electron charge 1.602×10^{-19} C



Physics and Radio-Electronics

The current flowing through the LED

$$I = \frac{V_S - V_D}{R_S}$$

V_S = Source voltage or supply voltage

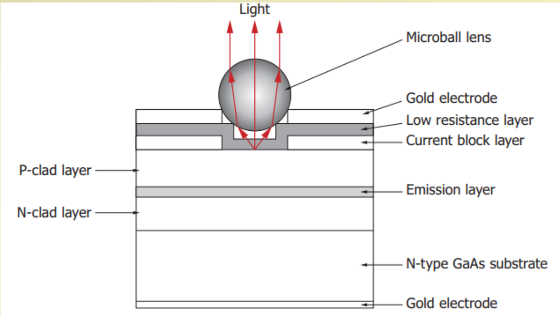
V_D = Voltage drop across LED

R_S = Resistor or current limiting resistor

LED - External quantum efficiency η_{ext}

It considers the number of photons actually leaving the LED structure

$$\eta_{ext} = \frac{Fn^2}{4n_x{}^2}$$



where
F = Transmission factor of the device-external interface
n = Light coupling medium refractive index
n_x = Device material refractive index

Loss mechanisms that affect the external quantum efficiency:

(1) Absorption within LED
(2) Fresnel losses: part of the light gets reflected back, reflection coefficient: $R=\{(n_2-n_1)/(n_2+n_1)\}$
(3) Critical angle loss: all light gets reflected back if the incident angle is greater than the critical angle.

LED - Power Efficiency

- Emitted optical power $$P_e = \frac{P_o F n^2}{4 n_x^2}$$

External power efficiency $$\eta_{ep} = \frac{p_e}{P} \times 100 \quad \%$$

The coupling efficiency

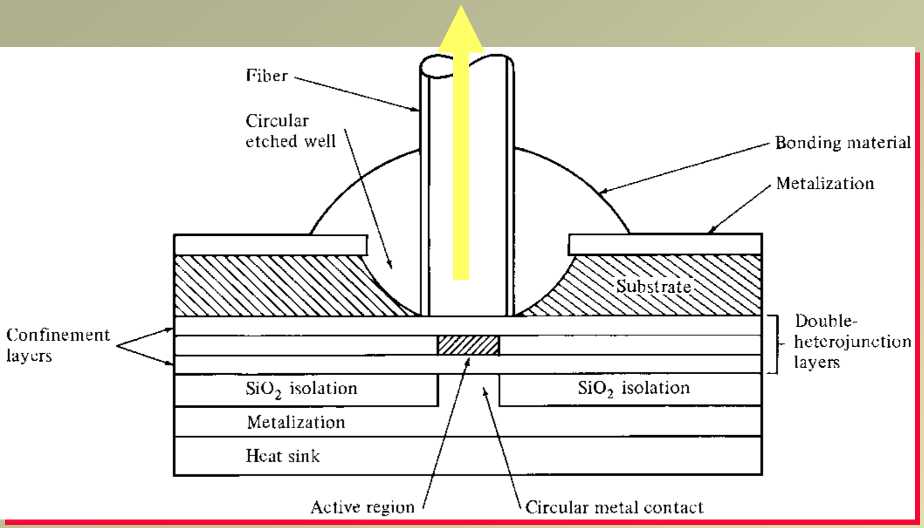
- MMSF: $\eta_c = NA^2$
- GMMF: $\eta_c = \frac{NA^2}{2}$

The optical coupling loss relative to P_e is : $$L_c = -10\log_{10}\frac{P_c}{P_e}$$

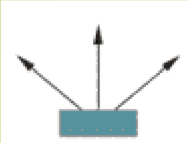
Or the power coupled to the fibre: $$P_c(\text{dBm}) = P_e(\text{dBm}) - L_c(\text{dB})$$

LED- Tyeps

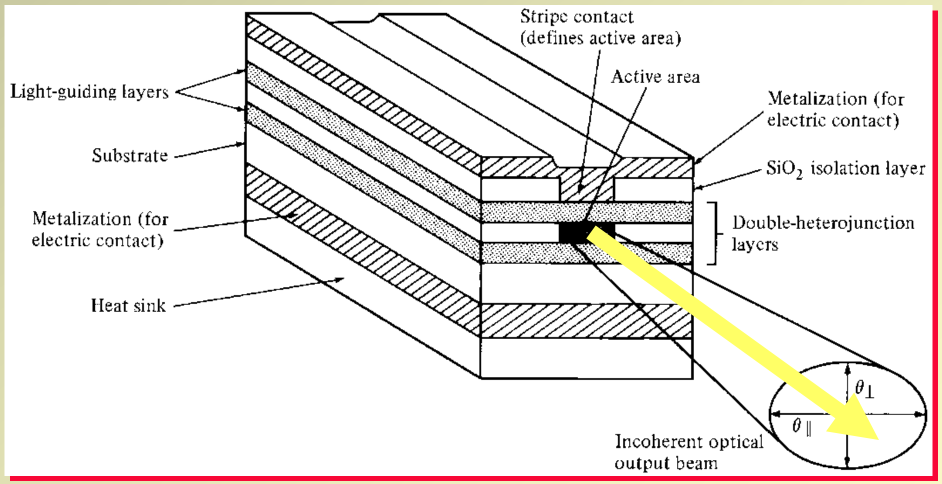
Surface Emitting LED (SLED)



- Data rates less than 20 Mbps
- Short optical links with large NA fibres (poor coupling)
- Coupling lens used to increase efficiency



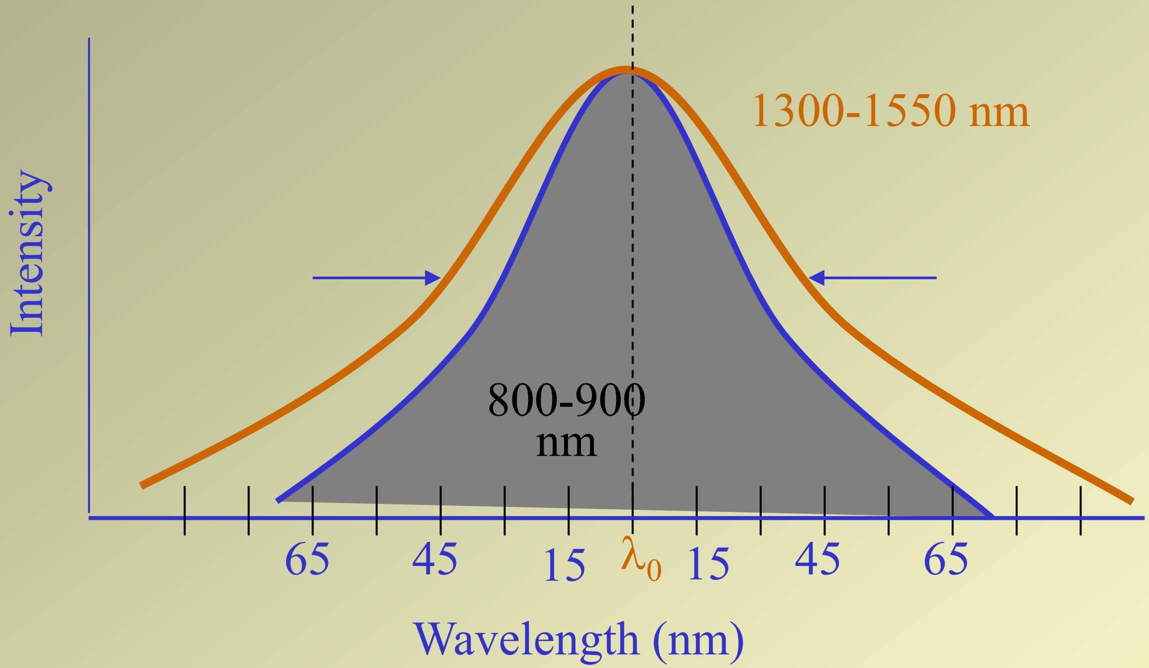
Edge Emitting LED (ELED)

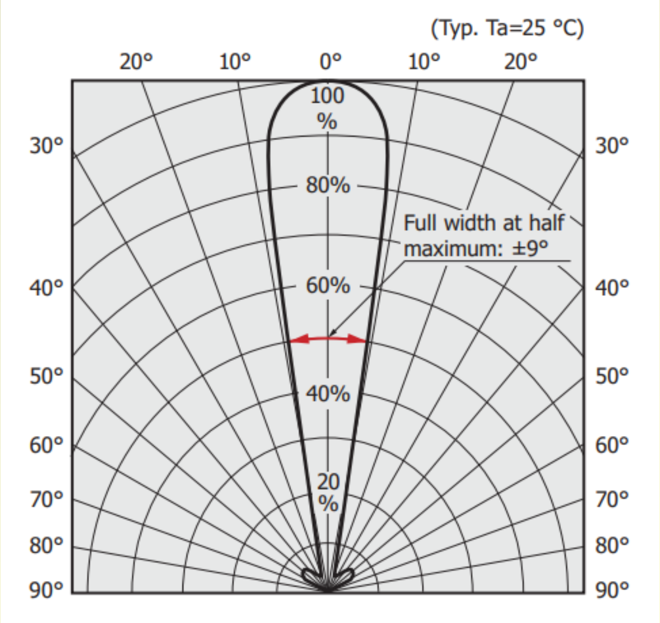


- Higher data rate > 100 Mbps
- Multimode and single mode fibres

G Keiser 2000

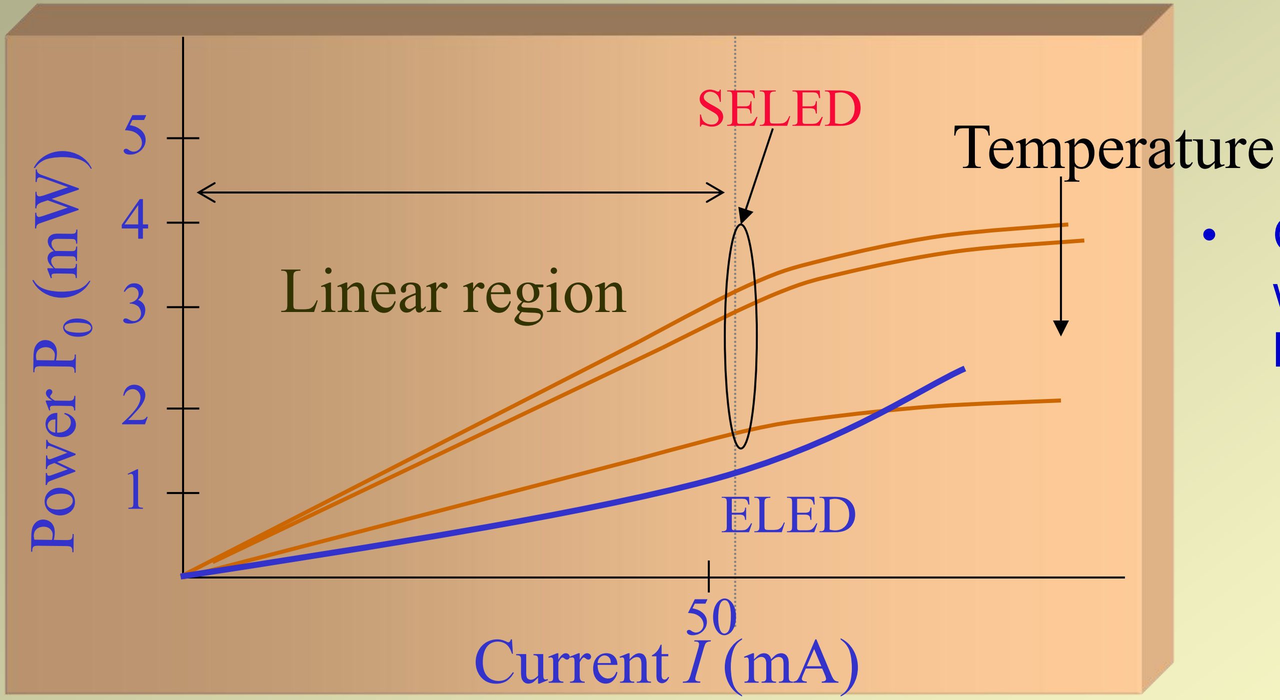
LED - Spectral Profile





Directivity

LED - Power Vs. Current Characteristics



- Output power decreases with age, Life time of 10^5 hours
  i.e. 3dB drop in optical power

Since $P \propto I$, then LED can be intensity modulated by modulating the I

LED - Characteristics

Wavelength	**800-850 nm**	**1300 nm**
• Spectral width (nm)	30-60	50-150
• Output power (mW)	0.4-5	0.4-1.0
• Coupled power (mW)		
- 100 um core	0.1-2 ELED 0.3-0.4 SLED	0.04-0.08
- 50 um core	0.01-0.05 SLED 0.05-0.15	0.03-0.07
- Single mode		0.003-0.04
• Drive current (mA)	20-150	100-150
• Modulation bandwidth (MHz)	80-150	100-300
Operating temperature	-65^0 to 125^0	

LED – Advantages and Disadvantages

- The brightness - Depends on the current flowing through the LED, and can be easily controlled by varying the current. This makes possible to operate LED displays under different ambient lighting conditions
- Low energy consumption
- Very cheap and readily available
- Light in weight and smaller size
- Longer lifetime
- Do not contain toxic material like mercury which is used in fluorescent lamps.
- Can emit different colours of light.

Disadvantages

- Need more power to operate than normal p-n junction diodes
- Low luminous efficiency
- Much lower speed than the laser diodes.

Laser - Characteristics

- The term Laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- Is an optical oscillator - Comprises a resonant optical amplifier whose output is fed back into its input with matching phase.

Any oscillator contains:

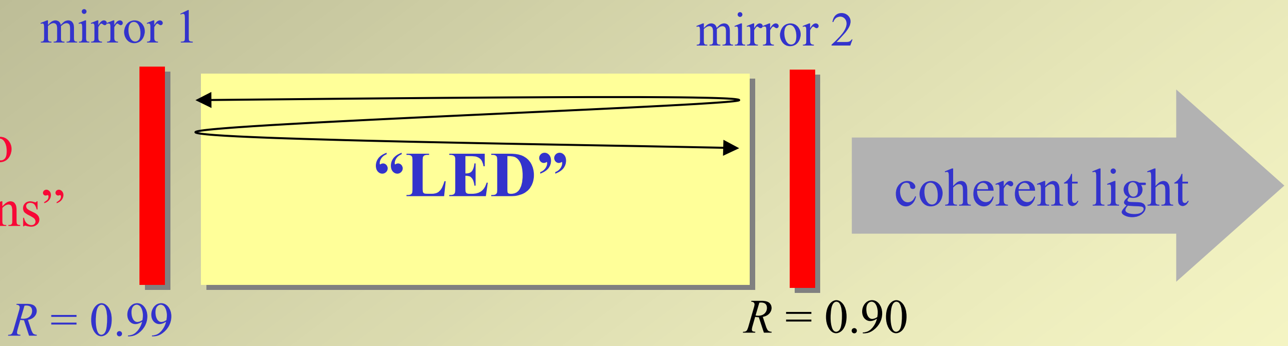
  - An amplifier with a gain-saturated mechanism
  - A feedback system
  - A frequency selection mechanism
  - An output coupling scheme

- Could be mono-chromatic (one colour), and is coherent in nature. (I.e. all the wavelengths contained within the Laser light have the same phase). One the main advantage of Laser over other light sources
- A pumping source providing power
- It had well defined threshold current beyond which lasing occurs
- At low operating current it behaves like LED
- Most operate in the near-infrared region

Laser - Basic Operation

Similar to LED, but based on **stimulated light emission**.

Mirrors used to "re-cycle" phonons"



mirror 1

mirror 2

"LED"

coherent light

$R = 0.99$

$R = 0.90$

Reflectivity $R = [(n-1)/(n+1)]^2$

Three steps required to generate a laser beam are:

- Absorption
- Spontaneous Emission
- Stimulated Emission

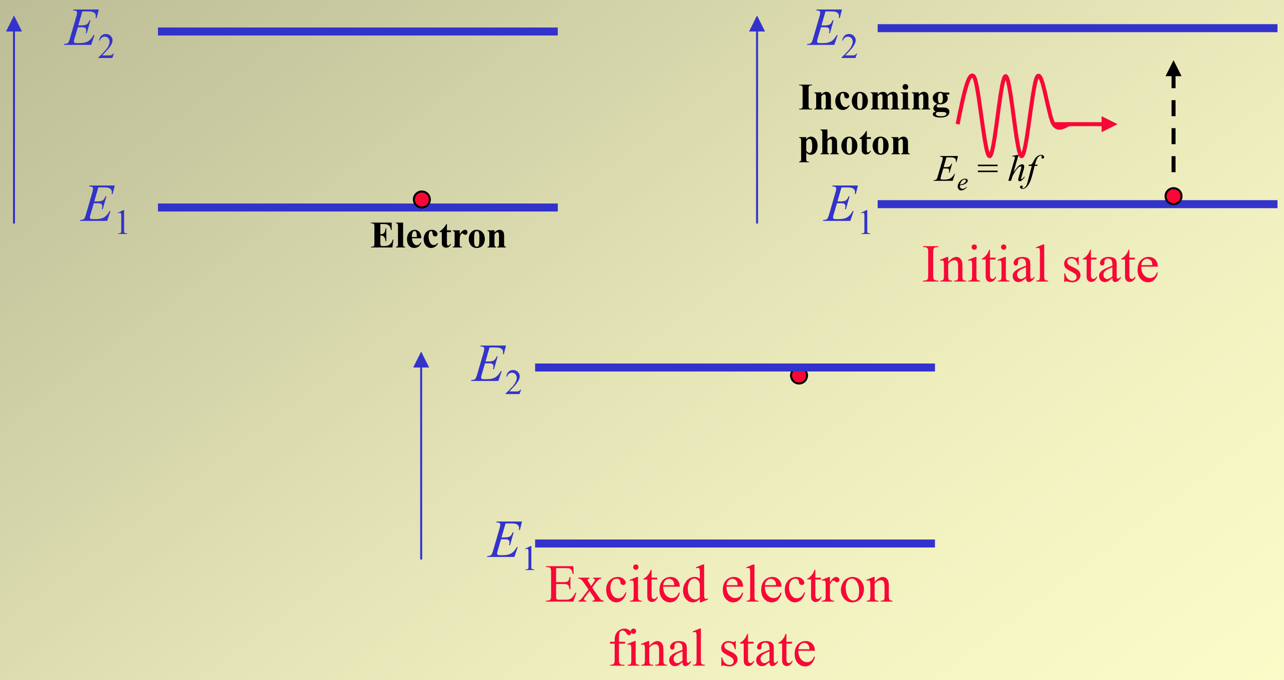
Current density:

- 10^4 A/cm2 down to 10 A/cm2

Absorption

When a photon with certain energy is incident on an electron in a semiconductor at the ground state(lower energy level E_1 the electron absorbs the energy and shifts to the higher energy level E_2.

The energy now acquired by the electron is $E_e = hf = E_2 - E_1$. Plank's law

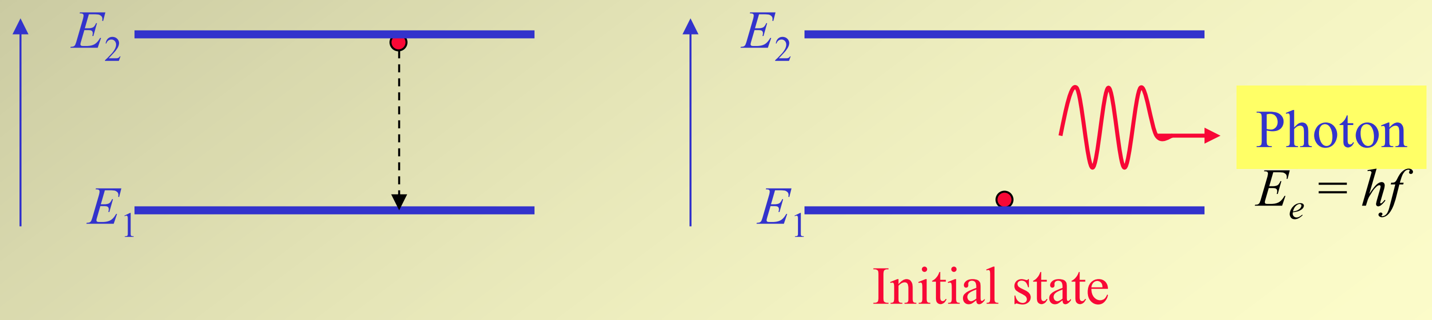


Initial state

Excited electron final state

Spontaneous Emission

- E_2 is unstable and the excited electron(s) will return back to the lower energy level E_1
- As they fall, they give up the energy acquired during absorption in the form of radiation, which is known as the spontaneous emission process.



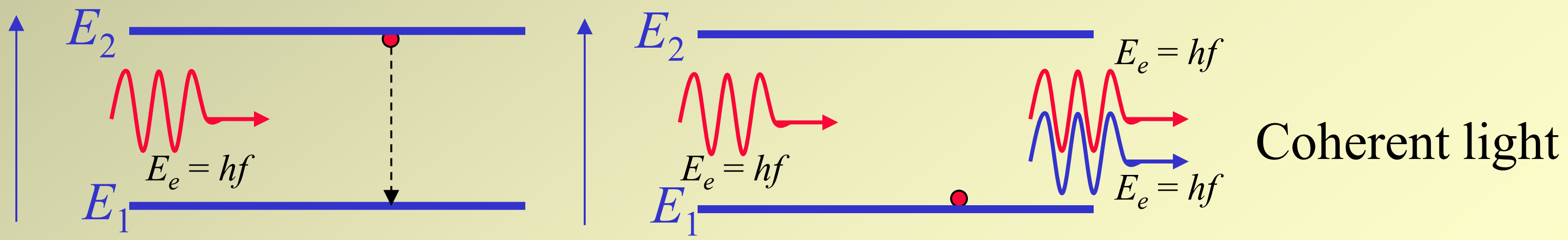
Stimulated Emission

- But before the occurrence of this spontaneous emission process, if external stimulation (photon) is used to strike the excited atom then, it will stimulate the electron to return to the lower state level.

- By doing so it releases its energy as a new photon. The generated photon(s) is in phase and have the same frequency as the incident photon.

- The result is generation of a coherent light composed of two or more photons.

- In quantum mechanic – Two process: Absorption and Stimulated emission



Requirement: $\alpha < 0$ ⇒ Light amplification: $I(x) = I_0\exp(-\alpha x)$

Laser - Basic Operation

So we have a large number of electron inside a cavity, therefore need to talk about statistics. Thus need to talk average rates of transition. I.e. what is the probability that a transition can take place between two levels per unit time.

The rate of absorption process is:

$$A_{1-2-abso} = \frac{dN_2}{dt} = B_{12}\overbrace{f_1(1\underbrace{-f_2}_{})}^{N_2}P(E_{21})$$

Transition probability from 1 to 2
[is a constant introduced by Einstein]

Occupation
probability of level 1

Photon density
In the cavity foe E_{21}

Probability that
Lower level is empty

f_1 and f_2 are Fermi functions given as:

$$f_1 = \frac{1}{e^{\frac{E_1-F_1}{kT}}+1}$$

$$f_2 = \frac{1}{e^{\frac{E_2-F_2}{kT}}+1}$$

F_1 and F_2 are quasi Fermi levels (i.e., number of electrons in the lower and upper levels, respectively

Laser - Basic Operation

The rate of spontaneous emission process is:

$$A_{21-Spon} = A_{21}f_2\underbrace{(1-f_1)}$$

Transition probability from 2 to 1
[is a constant introduced by Einstein]

Occupation
probability of level 2

Probability that
Lower level is empty

The rate of stimulated emission process is:

$$A_{21-Stim} = B_{21}f_2\underbrace{(1-f_1)}P(E_{21})$$

Transition probability
from 2 to 1

Photon density
In the cavity foe E_{21}

The rate of total emission process is (upper level is depopulated):

$$A_{1-2-emis} = -\frac{dN_2}{dt} = A_{21-spon} + A_{21-stim}$$

Laser - Basic Operation

- At dynamic equilibrium

Absorption = emission

$$A_{1-2-abso} = \frac{dN_2}{dt} = B_{12} f_1 (1 - f_2)\, P(E_{21})$$

$$A_{1-2-emis} = -\frac{dN_2}{dt} = A_{21-spon} + A_{21-stim}$$

One need to solve this to determine

$$P(E_{21})$$

The Rate Equations

Rate of change of photon numbers = stimulated emission + spontaneous emission + loss

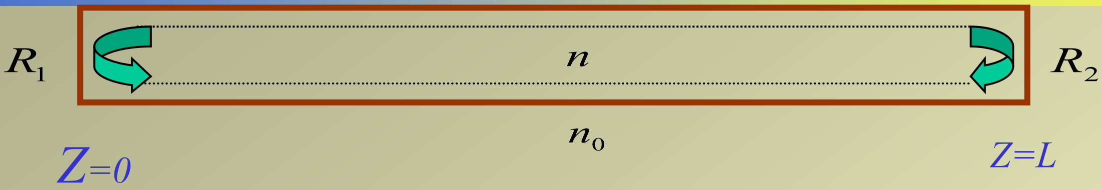
$$\frac{dN}{dt} = Cn_eN + R_{sp} - \frac{N}{\tau_{ph}}$$

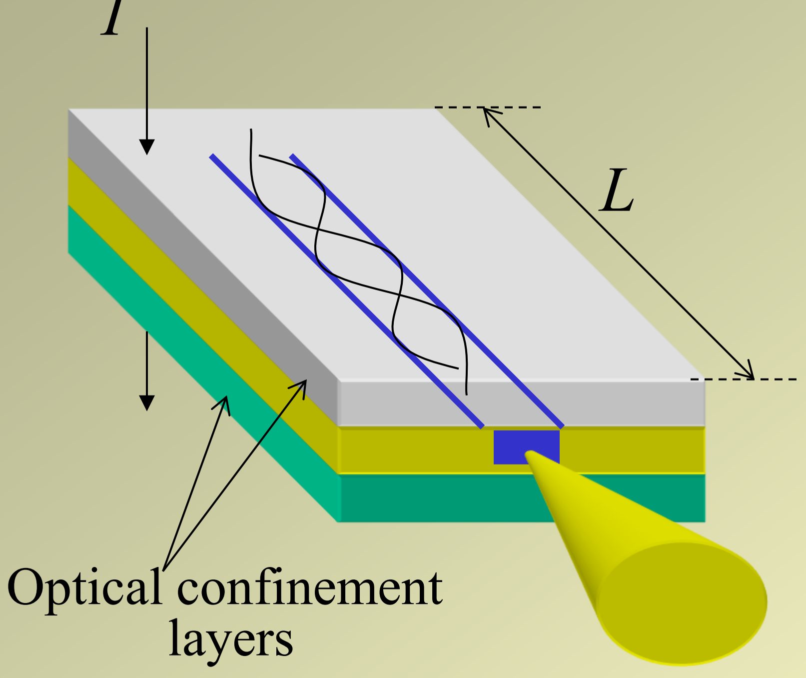
Rate of change of electron numbers = Injection + spontaneous emission + stimulated spontaneous

$$\frac{dn_e}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn_eN$$

N is photons per unit volume (optical output power), *J* is the current density, R_{sp} is the rate of spontaneous emission, τ_{ph} photon life time, *d* depth of the active Region, τ_{sp} spontaneous recombination rate, *C* is the constant, n_e injected electron per unit volume

Laser Diodes (LD)





Standing wave (modes) exists at frequencies for which

$$L = \frac{\lambda i}{2n}, \qquad i = 1, 2, ..$$

Modes are separated by

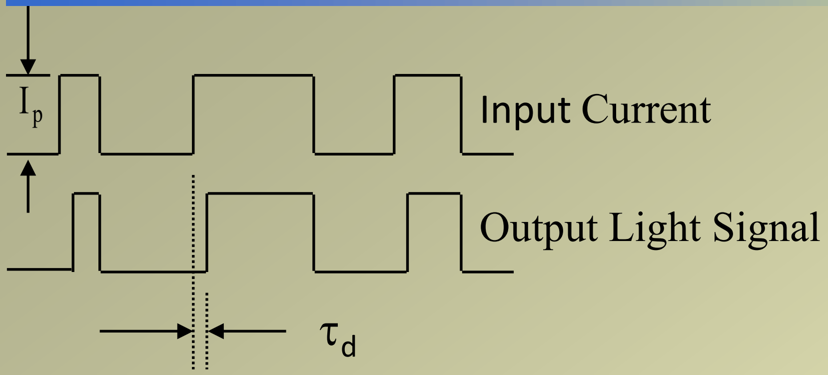
$$\delta f = \frac{c}{2nL}$$

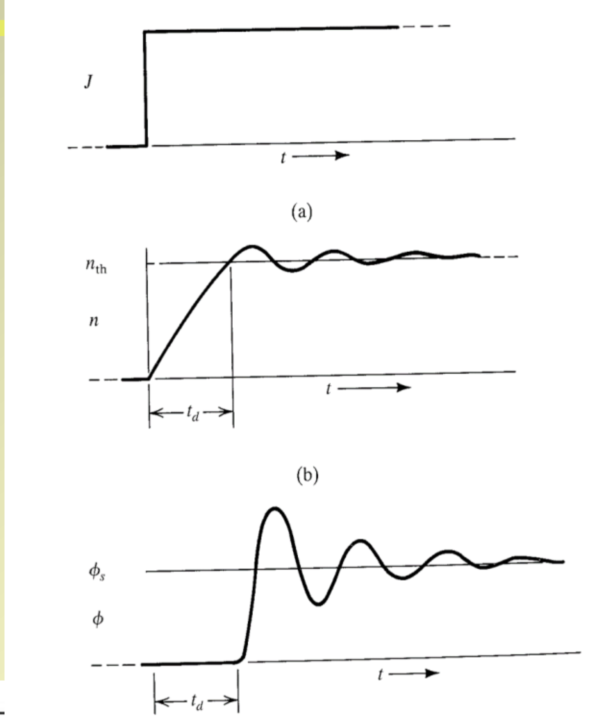
In terms of wavelength separation (Longitudinal mode spacing)

$$\Delta\lambda = \frac{2nL}{i} - \frac{2nL}{i+1} = \frac{2nL}{i} \qquad for\ i >> 1$$

$$\Delta\lambda = \frac{\lambda^2}{2nL} = \frac{\lambda^2}{c}\delta f$$

LD – Turn–on Delay





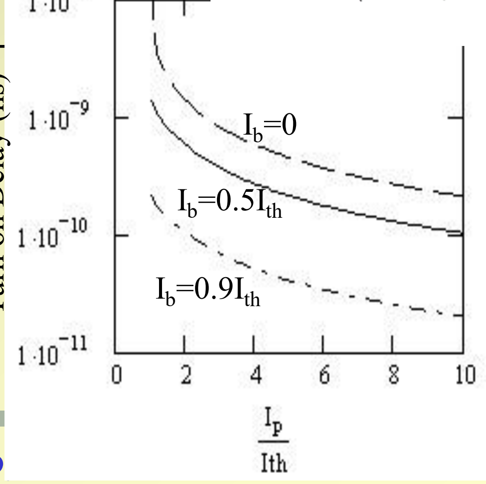
For and applied current pulse of amplitude I_p the turn on delay is given by:

$$\tau_d = \tau_{th} \ln\left(\frac{I_p}{I_p - I_{th}}\right)$$

with a bias current I_b applied:

$$\tau_d = \tau_{th} \ln\left(\frac{I_p}{I_p + I_b - I_{th}}\right)$$

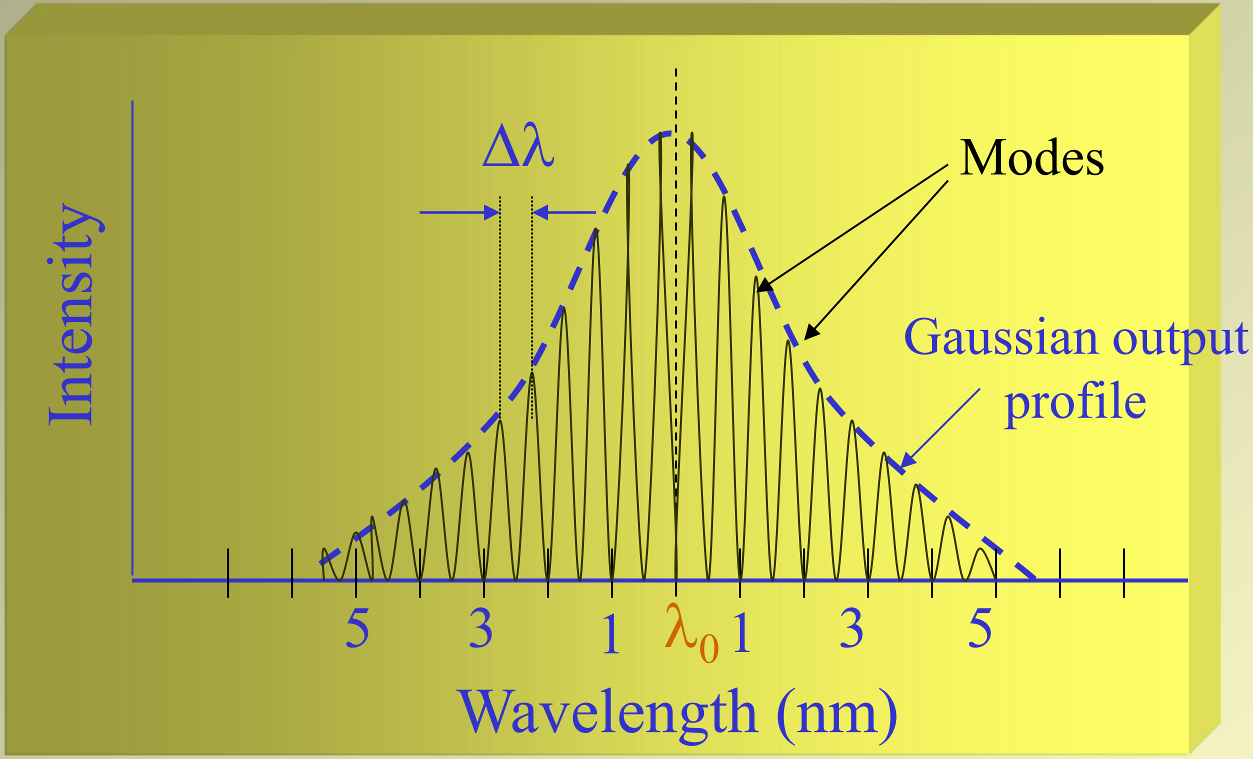
where τ_{th} is the delay at threshold (2ns

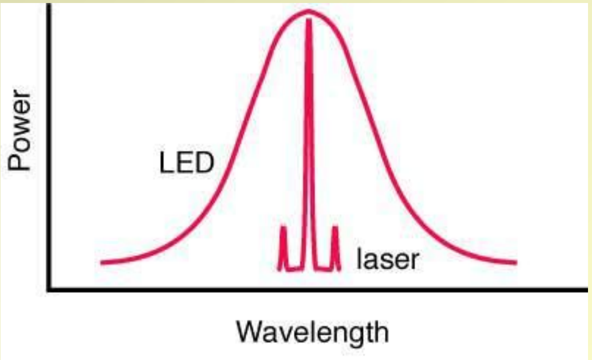


To reduce the turn on delay:

- Use a low threshold laser and make I_p large
- Bias the laser at or above threshold

LD - Spectral Profile





Multi-mode

LD - Efficiencies

Internal quantum efficiency

$$\eta_{\text{int}} = \frac{number\,of\ photons\,generated\,in\,the\,cavity}{number\,of\,injected\,electrons}$$

External quantum efficiency $\eta_{ext} = \frac{P_e}{IE_g}$

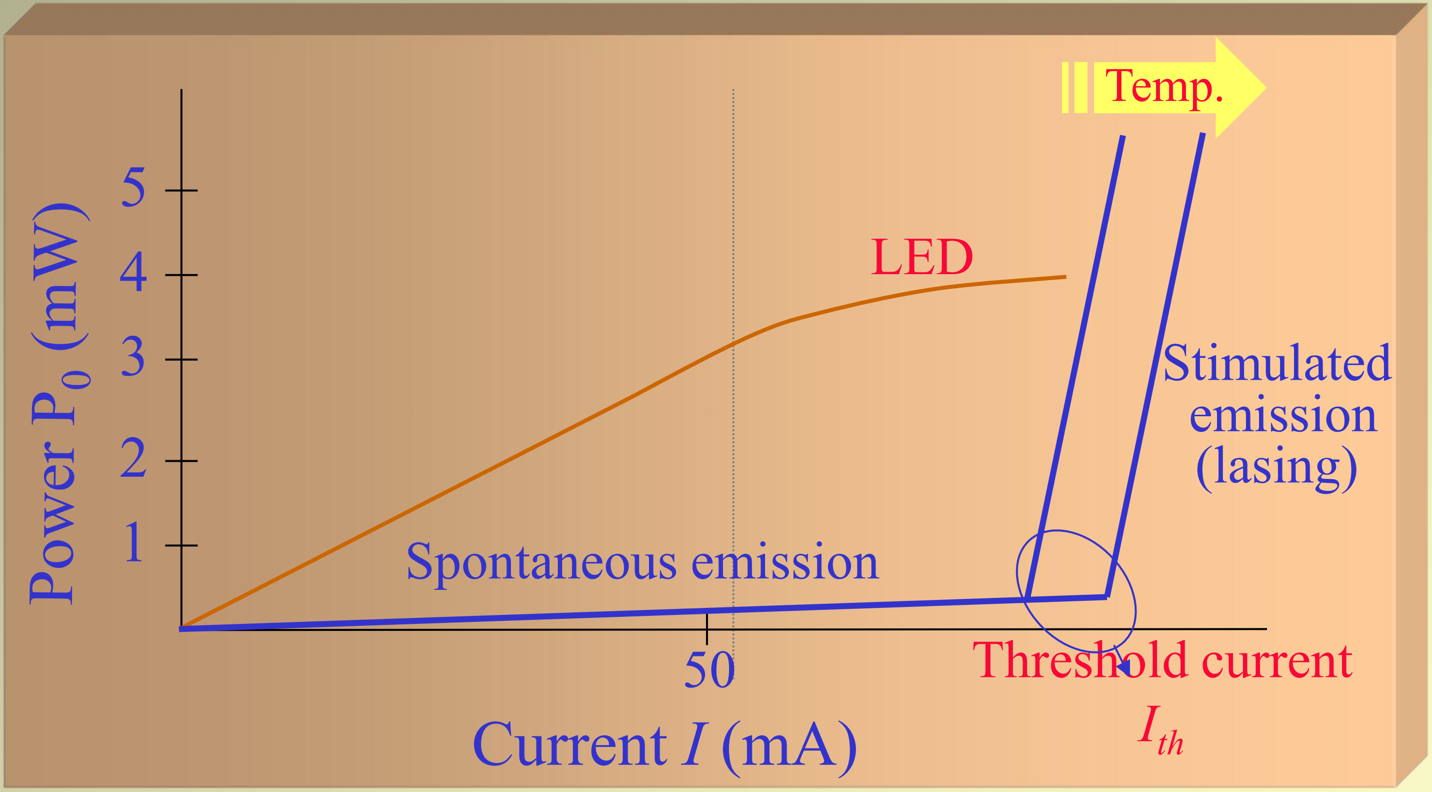
External power efficiency $\eta_{ep} = \frac{P_e}{P}$

Where $P = IV$

Power degradation over time $P = P_0 e^{-t/\tau_D}$

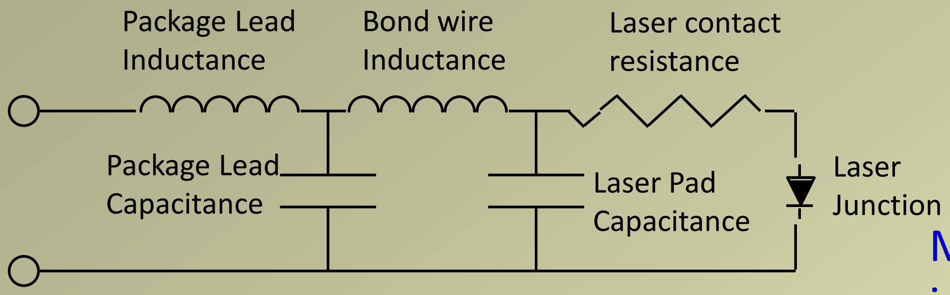
Lifetime decreases with current density and junction temperature

Power Vs. Current Characteristics



- Applying a bias current has the same effect as applying a pump laser; electrons are promoted to conduction band. F_c and F_v get farther apart as well
- Increasing the temperature creates a population distribution rather than a sharp cutoff near the Fermi levels

LD – Electrical Model



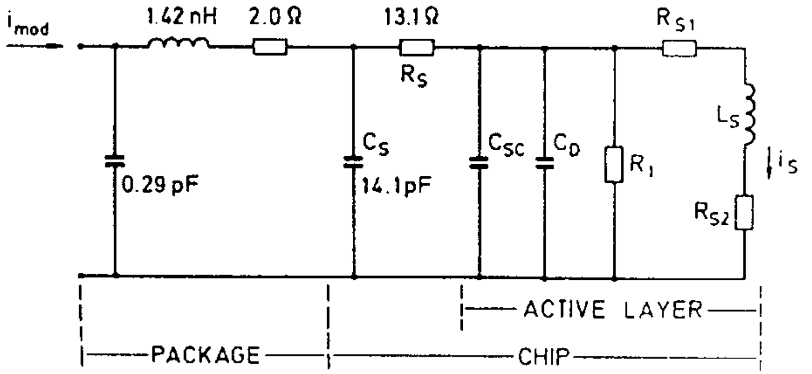
Simple large signal model

Use a large signal diode model for the laser junction, this neglects the optical resonance

More exactly the laser rate equations can be implemented in SPICE to give the correct transient behavior under large signal modulation

Assume that the light output is proportional to the current through the laser junction

Small signal model



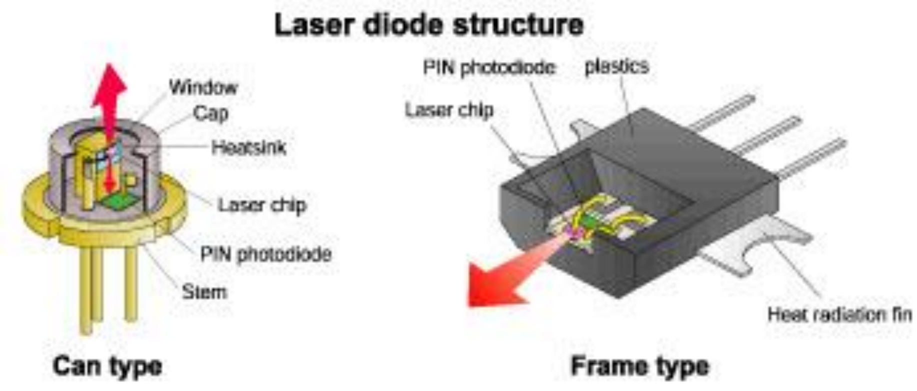
I (mA)	C_{SC}(pF)	C_D(pF)	R_1(Ω)	R_{S1}(mΩ)	R_{S2}(μΩ)	L_S(pH)
20	10	380	1.23	23.4	34.0	7.07
25	10	381	0.829	24.1	11.8	4.19
30	10	382	0.628	24.7	6.0	3.01

Small signal equivalent circuit of a packaged BH laser HLP 3400.[32]

(Hitachi)

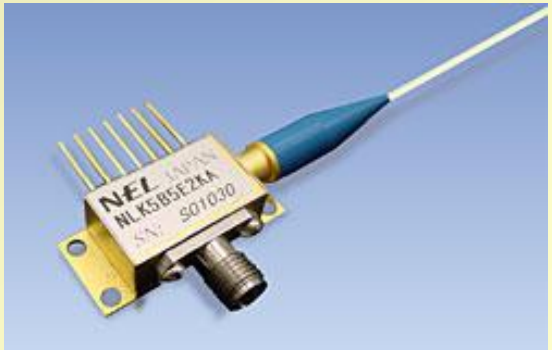
LD - Single Mode

- Achieved by reducing the cavity length *L* from 250 μm to 25 μm
- But difficult to fabricate
- Low power
- Long distance applications



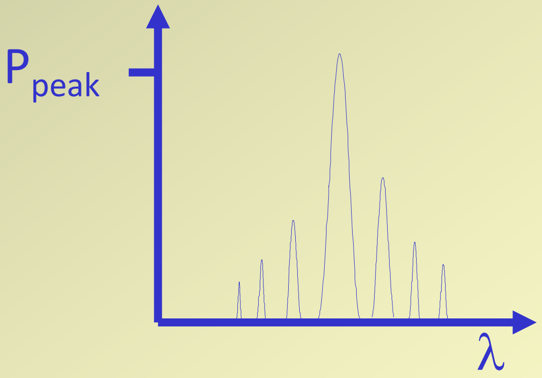
Types:

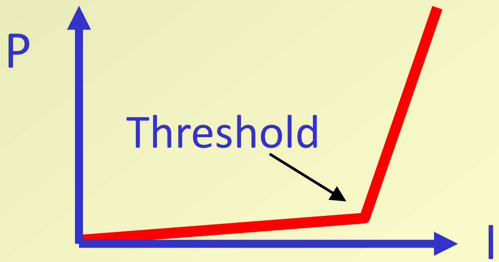
- Fabry-Perot (FP)
- Distributed Feedback (DFB)
- Distributed Bragg Reflector (DBR)
- Distributed Reflector (DR)

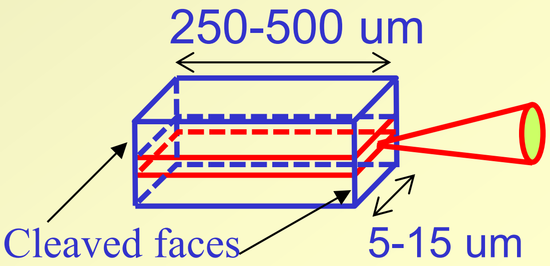


Laser - Fabry-Perot

- Strong optical feedback in the longitudinal direction
- Multiple longitudinal mode spectrum
- "Classic" semiconductor laser
  - 1st fibre optic links (850 nm or 1300 nm)
  - Short & medium range links
- Key characteristics
  - Wavelength: 850 or 1310 nm
  - Total output power: a few mw
  - Spectral width: 3 to 20 nm
  - Mode spacing: 0.7 to 2 nm
  - Highly polarized
  - Coherence length: 1 to 100 mm
  - Small NA (→ good coupling into fiber)







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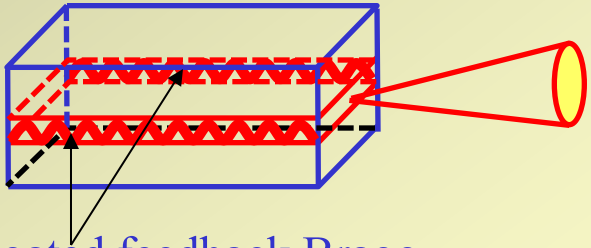
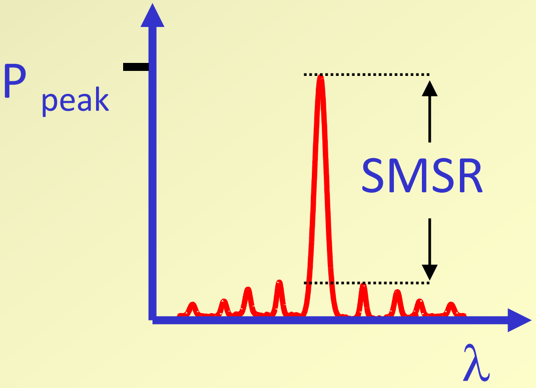
Laser - Distributed Feedback (DFB)

- No cleaved faces, uses Bragg Reflectors for lasing
- Single longitudinal mode spectrum
- High performance
  - Costly
  - Long-haul links & DWDM systems
- Key characteristics
  - Wavelength: around 1550 nm
  - Total power output: 3 to 50 mw
  - Spectral width: 10 to 100 MHz (0.08 to 0.8 pm)
  - Sidemode suppression ratio (SMSR): > 50 dB
  - Coherence length: 1 to 100 m
  - Small NA (→ good coupling into fiber)





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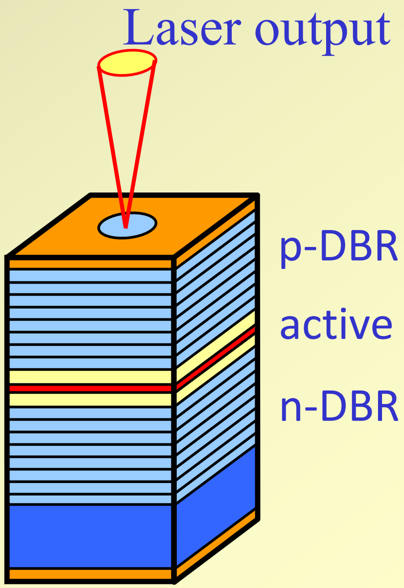
Laser - Vertical Cavity Surface Emitting Lasers (VCSEL)

- Distributed Bragg reflector mirrors
  - Alternating layers of semiconductor material
  - 40 to 60 layers, each $\lambda / 4$ thick
  - Beam matches optical acceptance needs of fibers more closely
- Key properties
  - Wavelength range: 780 to 980 nm (gigabit ethernet)
  - Spectral width: <1nm
  - Total output power: >-10 dBm
  - Coherence length:10 cm to10 m
  - Numerical aperture: 0.2 to 0.3



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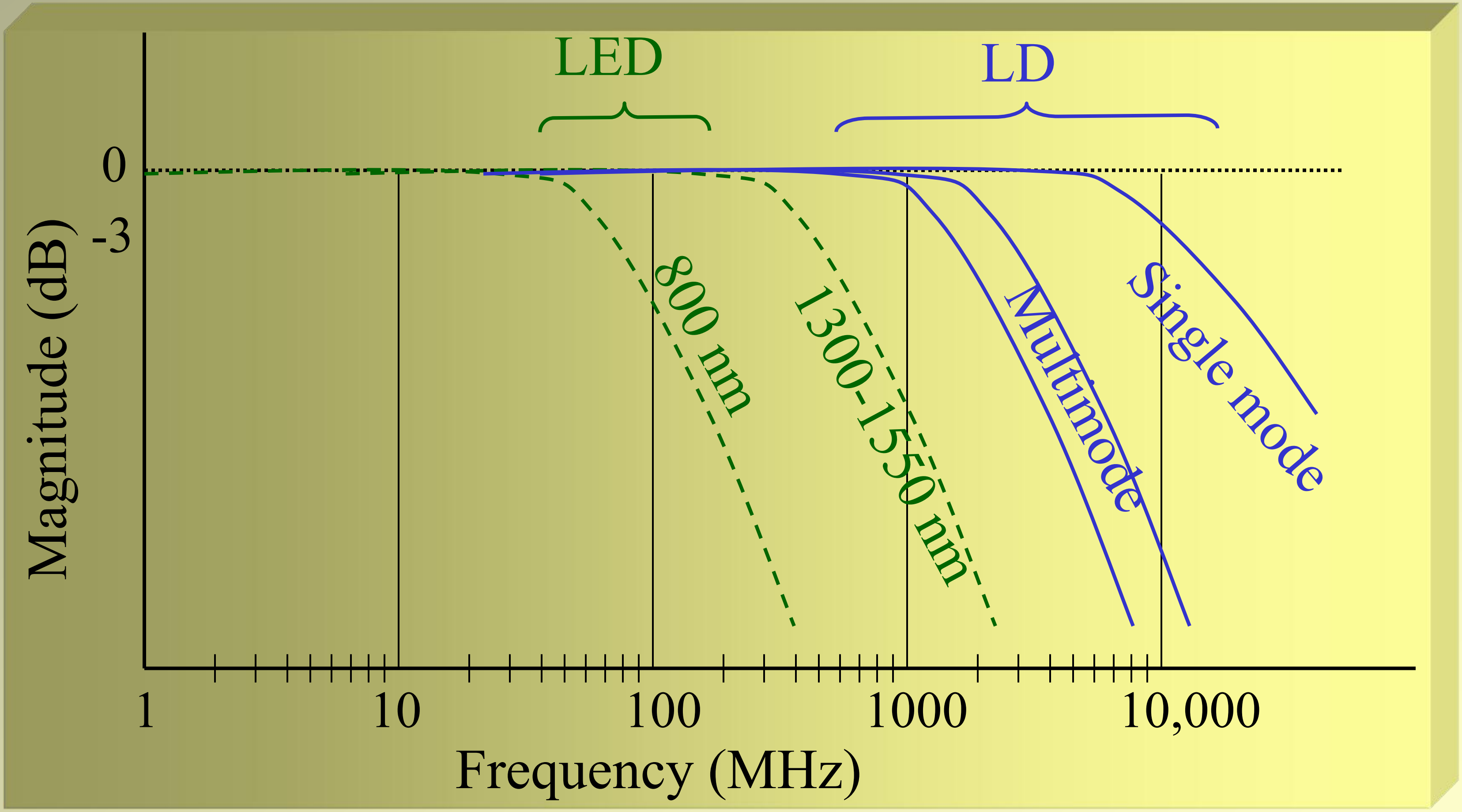
Laser diode - Properties

Property	Multimode	Single Mode
• Spectral width (nm)	1-5	< 0.2
• Output power (mW)	1-10	10-100
• Coupled power (μW) - Single mode	0.1-5	1-40
• External quantum efficiency	1-40	25-60
• Drive current (mA)	50-150	100-250
• Modulation bandwidth (MHz)	2000	6000-40,000

LED - Frequenct Response



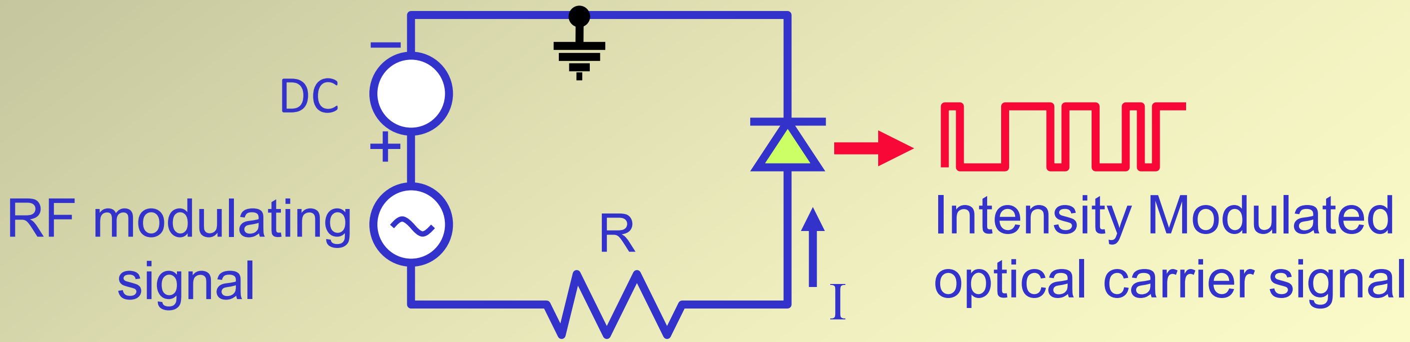
Comparison

Characteristics	LEDs	Lasers
Output Power	Linearly proportional to drive current	Proportional to current above the threshold
Current	Drive Current: 50 to 100 mA Peak	Threshold Current: 5 to 40 mA
Coupled Power	Moderate	High
Speed	Slower	Faster
Output Pattern	Higher	Lower
Bandwidth	Moderate	High
Wavelengths Available	0.66 to 1.65 µm	0.78 to 1.65 µm
Spectral Width	Wider (40-190 nm FWHM)	Narrower (0.00001 nm to 10 nm FWHM)
Fiber Type	Multimode Only	SM, MM
Ease of Use	Easier	Harder
Lifetime	Longer (10^7 Hours)	Long
Cost	Low ($5-$300)	High ($100-$10,000)

Modulation

The process transmitting information via light carrier (or any carrier signal) is called modulation.

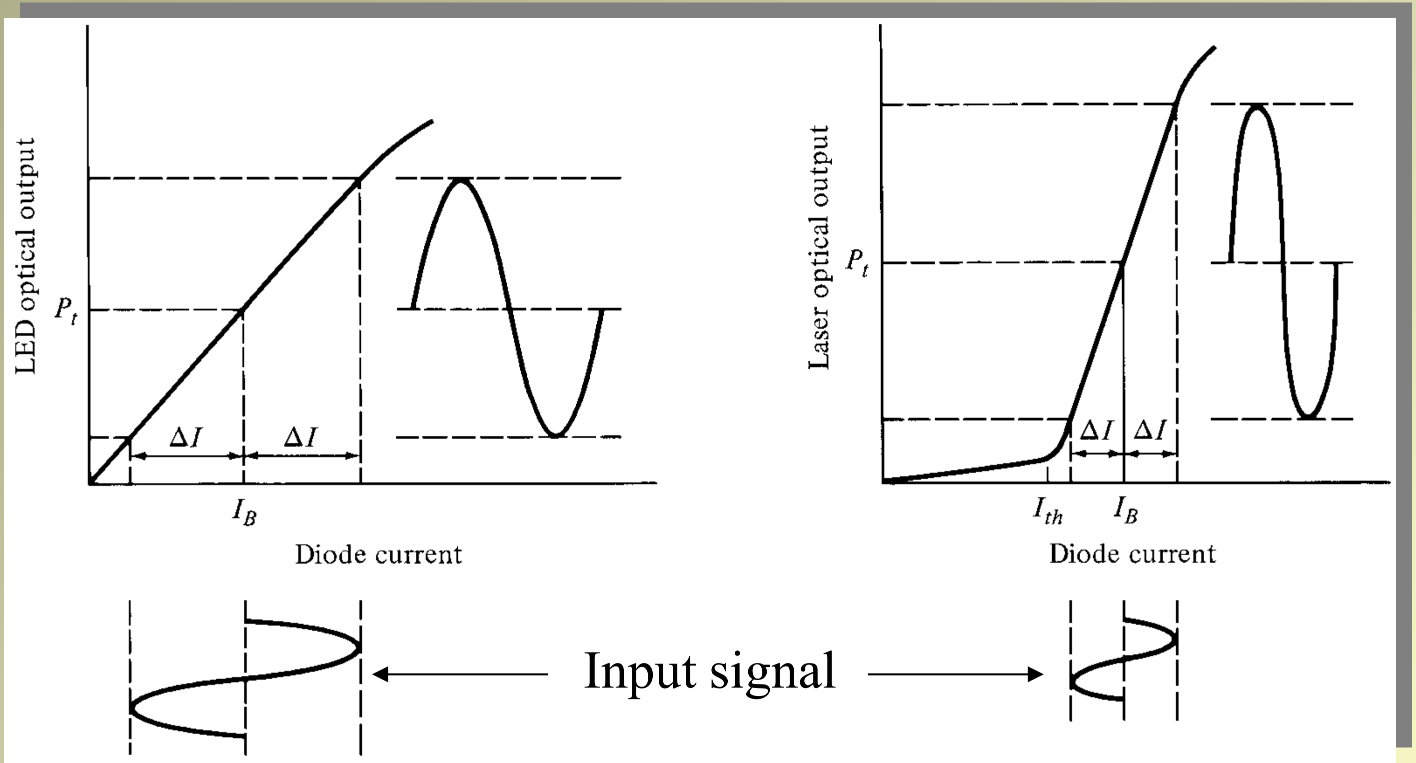
- **Direct Intensity (current)**
  - Inexpensive (LED)
  - In LD it suffers from chirp up to 1 nm (wavelength variation due to variation in electron densities in the lasing area)



- **External Modulation**

Direct Intensity Modulation- Analogue

LED **LD**



Modulation Index
M = $\Delta I / I_B'$

For LED $I_B' = I_B$

For LD
$I_B' = I_B - I_{th}$

With no input signal m(t) the optical output $P(t) = P_t[1 + M\,\mathrm{m}(t)$,

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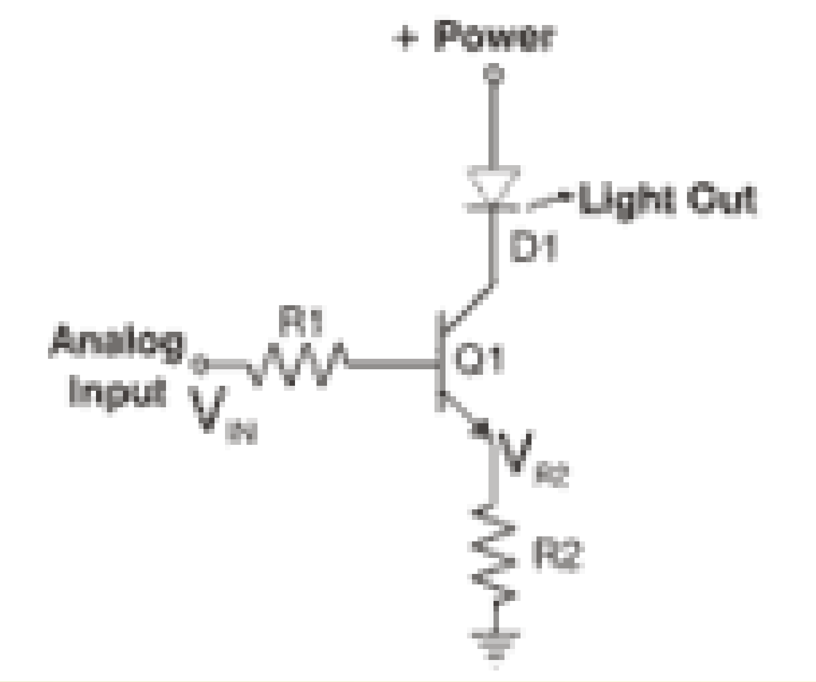
Direct Intensity Modulation- Analogue

- Simple
- Referred to as a **transconductance amplifier -** converts a *V*→ *I*.
- R1: prevents oscillations in Q1.
- A drawback –
  - The base capacitance varies with the base voltage, which introduces nonlinearities that limit the circuits linearity.

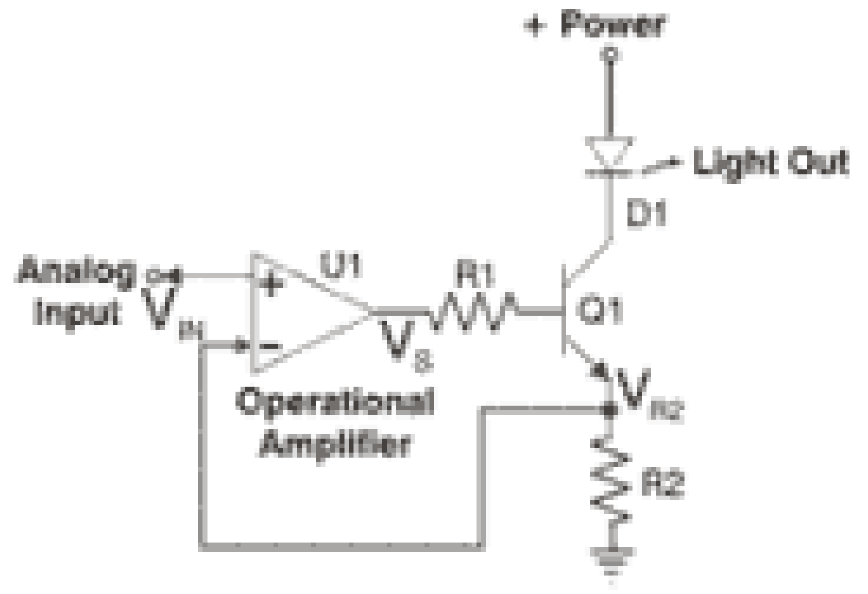


$$I_d = \left(\frac{V_{in} - 0.6}{R_2}\right) \cdot \left(\frac{\beta}{\beta + 1}\right)$$

http://www.fiber-optics.info/articles/light-emitting_diode_led

Direct Intensity Modulation- Analogue

- Moderate performance
- The linearized eliminates most of the nonlinearities associated with Q1.
- U1 forms a feedback loop that drives the base of Q1 in such a way that assures that V_{R2} equals V_{IN}.
- Still experiences some lesser nonlinearities associated with Q1, but these do not represent the limiting factor.
- Note, the delay due to the feedback in U1, which limits the bandwidth to about 10-100 MHz.

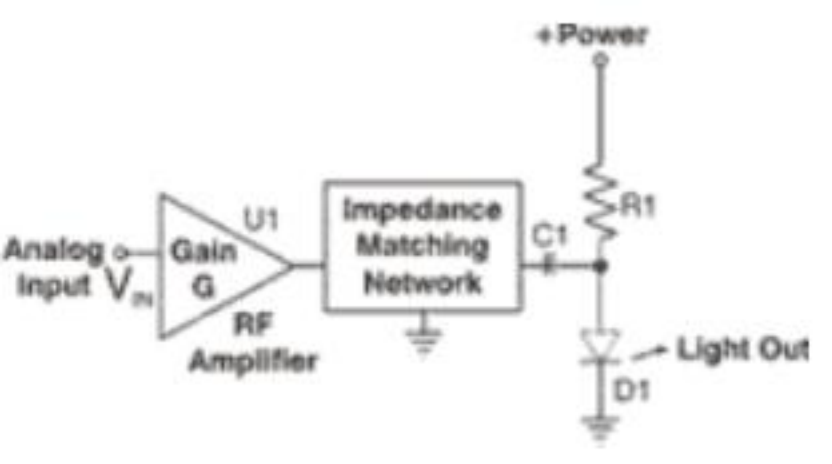


$$I_d = \left(\frac{V_{in}}{R_2}\right)\cdot\left(\frac{\beta}{\beta+1}\right)$$

http://www.fiber-optics.info/articles/light-emitting_diode_led

Direct Intensity Modulation- Analogue

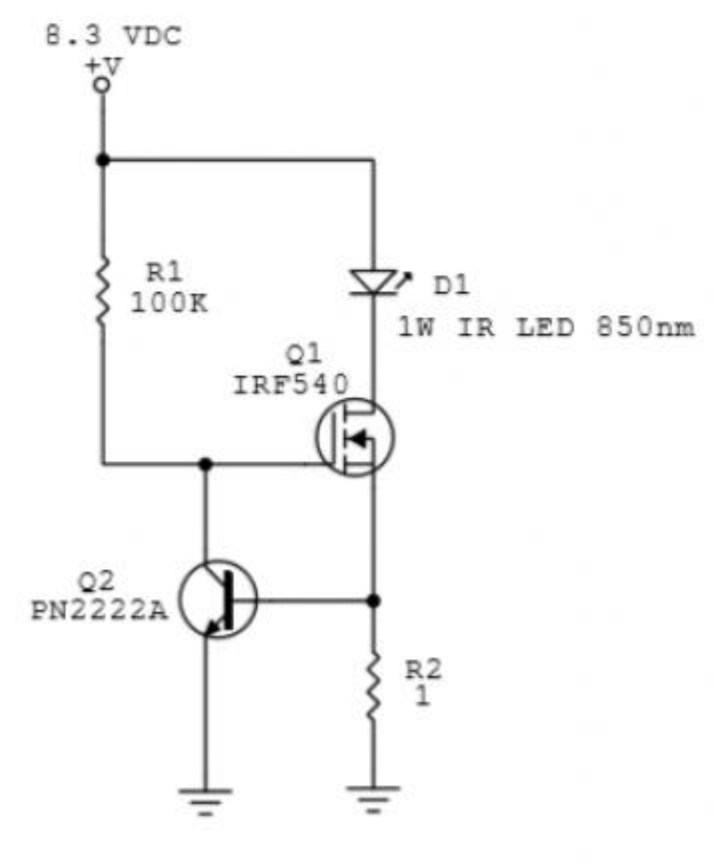
- Highest performance.
- R1 supplies the DC current through D1. Sometimes, a constant current source or a network that includes temperature compensation replaces R1.
- A wideband RF amplifier, U1, serves two purposes:
  - amplifies V_{IN} to allow the use of a small input signal.
  - isolates the LED from the input circuit, so impedance matching at the input, V_{IN}, which reduces reflections. The output of U1 is usually 50 Ohms or 75 Ohms.
- C1 - Block any DC.

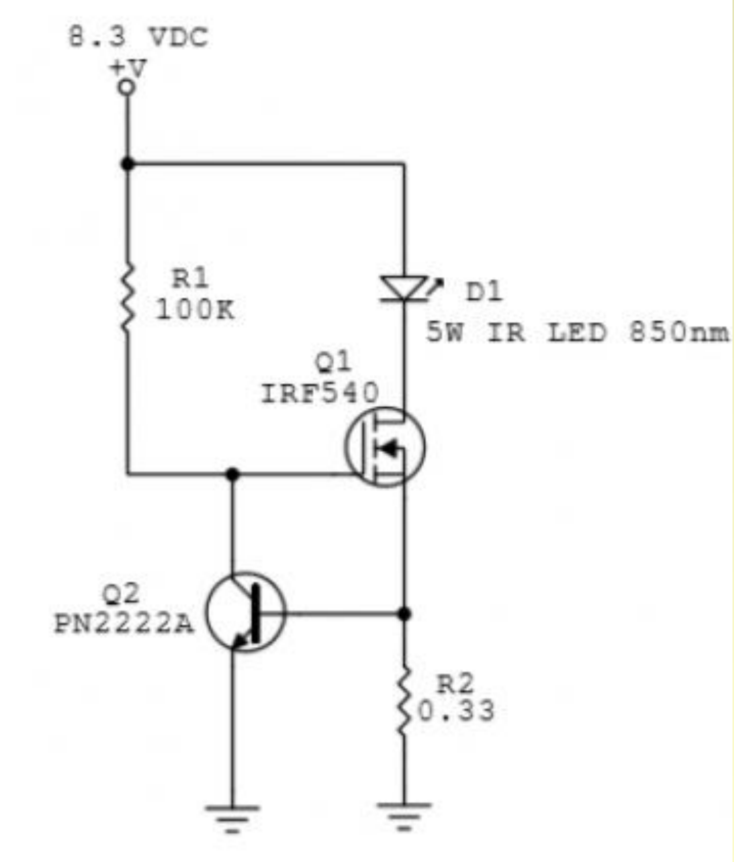


A typical LED may have an input impedance ranging from 5 Ohms to 10 Ohms. An impedance matching network is inserted between the amplifier and D1.

http://www.fiber-optics.info/articles/light-emitting_diode_led

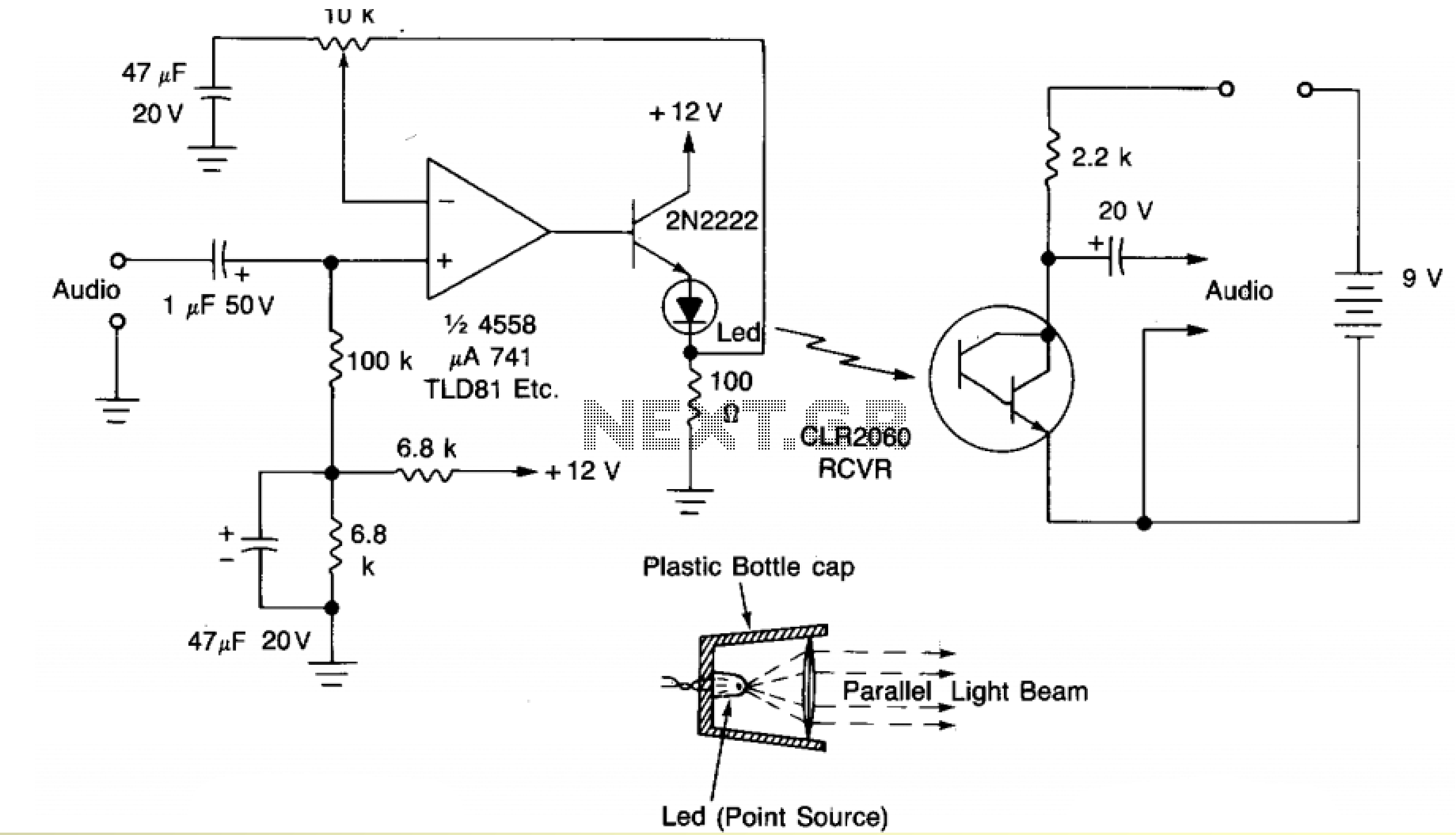
Direct Intensity Modulation- Analogue





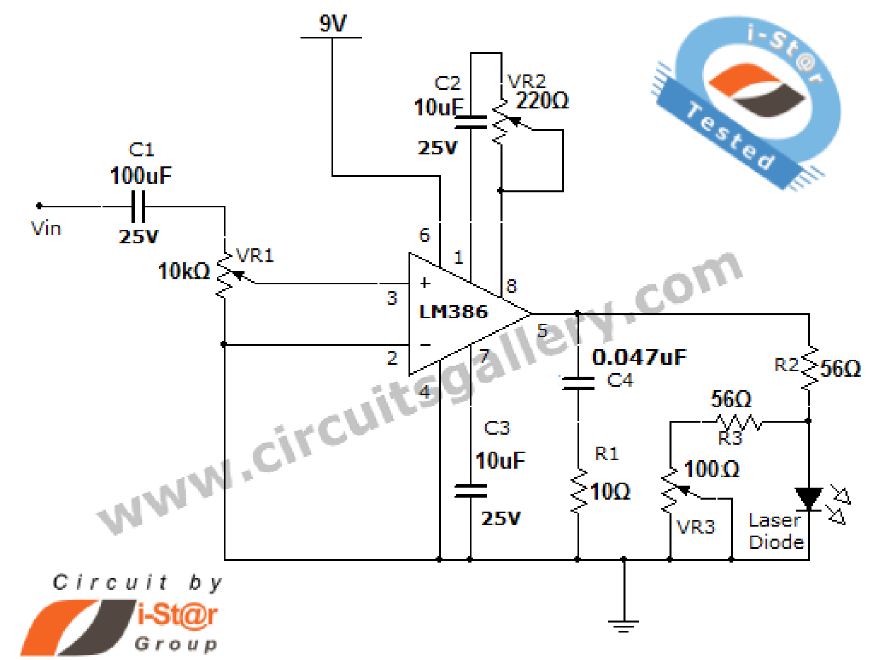
Q1 is turned on by R1 and acts as a variable resistor. Q2 is an “over-current” switch and R2 sets the maximum current.

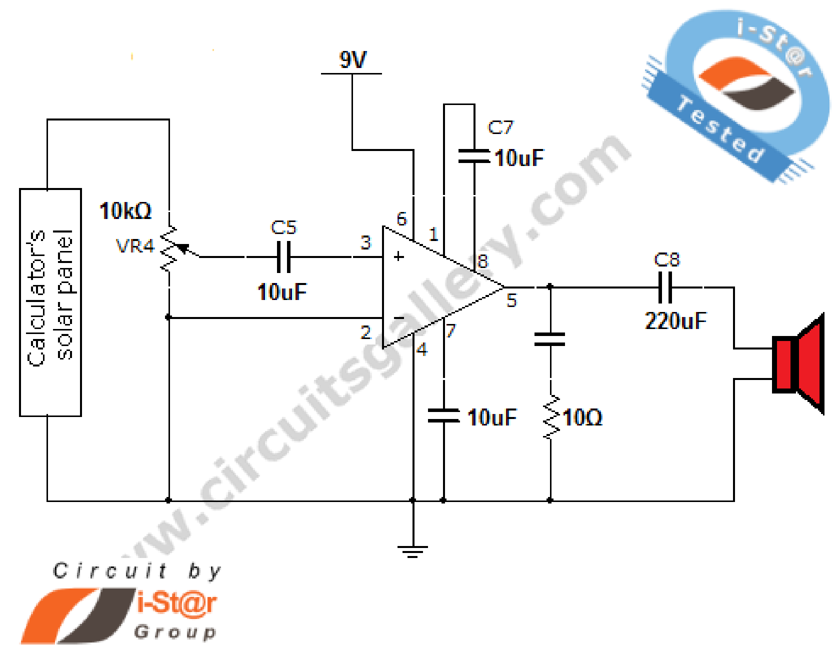
Direct Intensity Modulation- Digital



http://www.next.gr/light-laser-led/led-circuits/optical-communication-system-l12211.html

Direct Intensity Modulation- Analogue

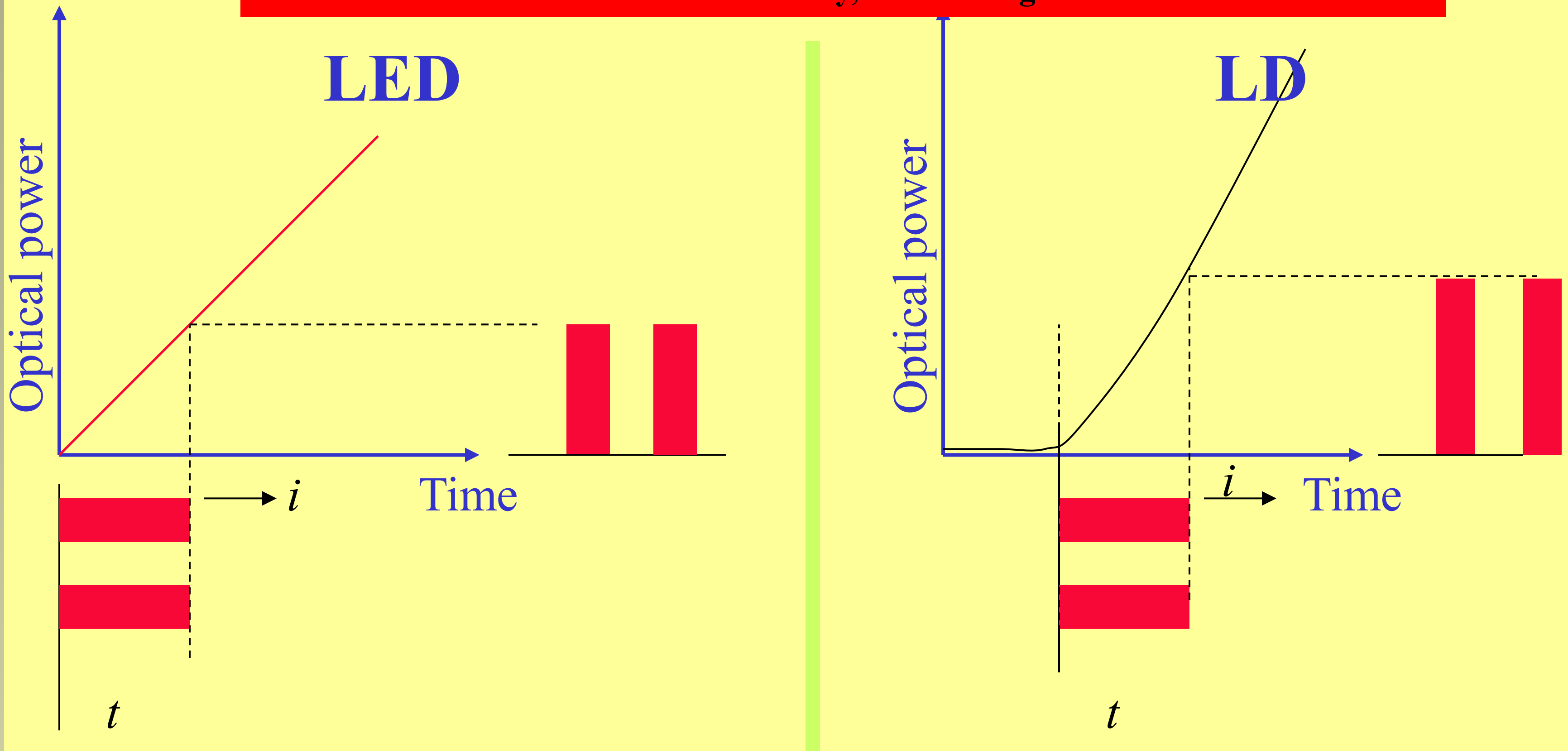




http://circuitsgallery.blogspot.co.uk/2012/06/laser-communication-project-circuit.html

Direct Intensity Modulation- Analogue

- **No concern about LED linearity, since the light is either ON or OFF**

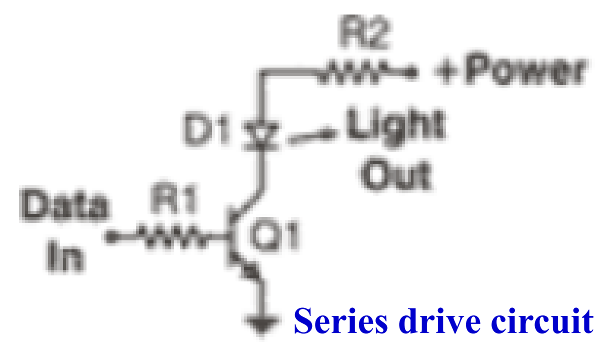


In a pulse modulated laser, if the laser is completely turned off after each pulse, after onset of the current pulse, a time delay is given by:

$$t_d = \tau \ln\left[\frac{I_p}{I_p + (I_B - I_{th})}\right]$$

τ : carrier life time, I_p : Current pulse amplitude, I_B : Bias current

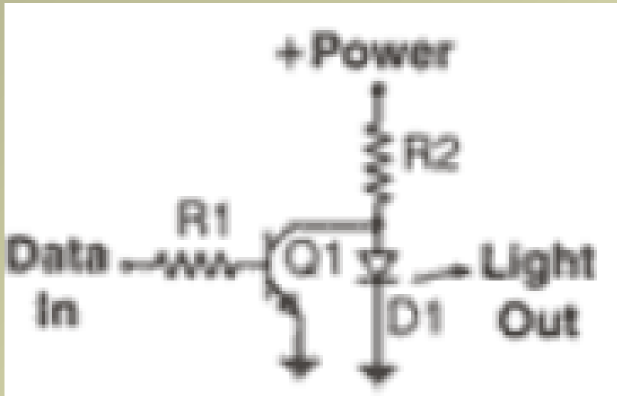
Direct Intensity Modulation- Digital



Series drive circuit

- Simple driver circuit.
- The transistor is a switch
- The key disadvantage –
  - Low speed.
  - This type of driver circuit is rarely used at data rates above 30-50 Mb/s.

$$I_d = \left(\frac{V_{cc} - V_{fd} - V_{ce}}{R_2}\right)$$

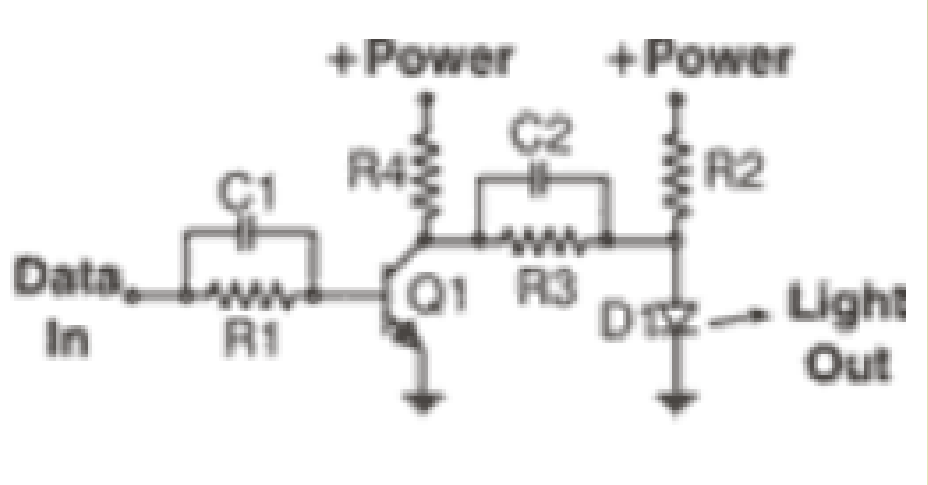


Shunt drive circuit

Power dissipation - Double that of the series driver

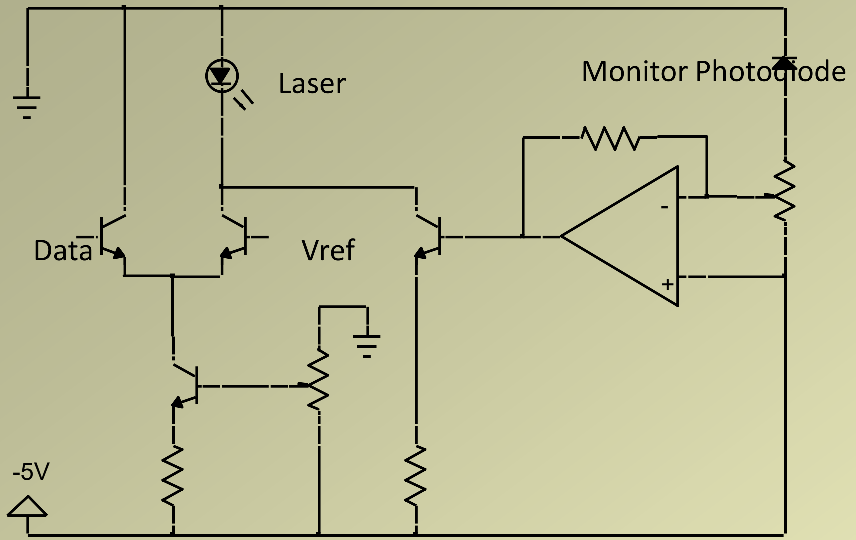
- Higher speed.
- Uses Q1 to quickly discharge the LED to turn it off.
- Note: LED's are easy to turn on quickly, but are difficult to turn off because of the relatively long carrier lifetime.
  - In the shunt driver circuit, R2 (typicall 40- 1k Ohms) provides a positive current to turn on the LED.
  - Q1 provides the turnoff current. When saturated, Q1 will have an impedance of a few Ohms. This provides a much larger discharging current allowing the LED to turn off quickly.

Direct Intensity Modulation- Digital

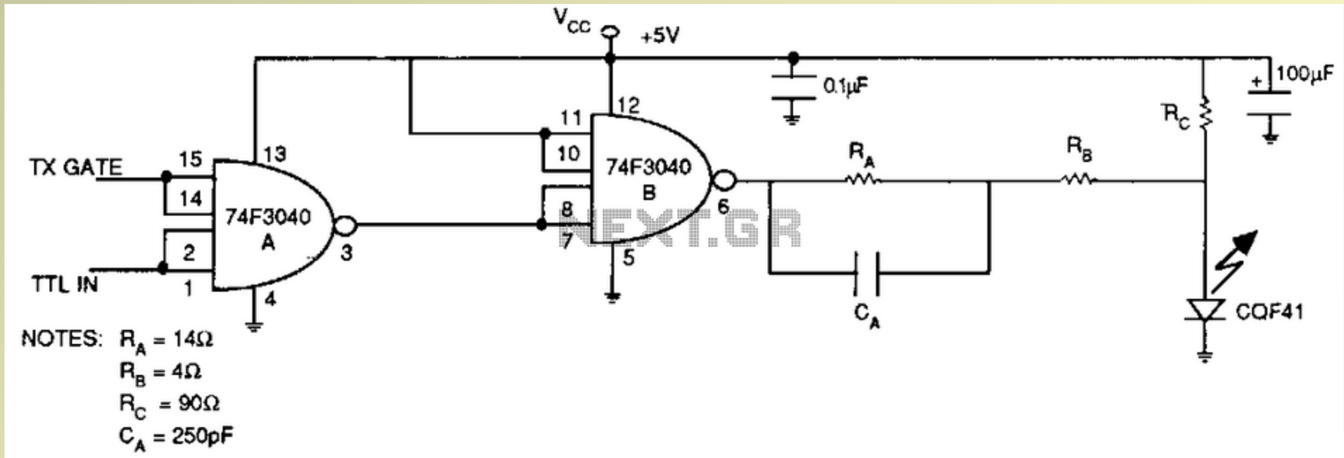


- Much faster.
- C1 - to improve the turn-on and turnoff characteristics of Q1.
    - C1 should not be too large. If this occurs, Q1 base may be overdriven and damaged.
- R3 and R4 and capacitor C2 - Provide overdrive when the LED is turned on and underdrive when Q1 is turned off.
    - The overdrive and underdrive accelerates the LED transitions.
    - Typically, the RC time constant of R3 and C2 is made ~ approximately equal to the rise or fall time of the LED.

Direct Intensity Modulation- Digital



Average number of 1s and 0s (the "Mark Density") is linearly related to the average power. If this duty cycle changes then the bias point will shift



NOTES: R_A = 14Ω
R_B = 4Ω
R_C = 90Ω
C_A = 250pF

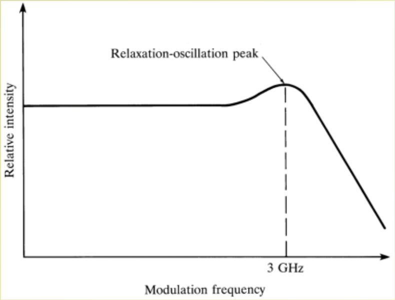
Direct Intensity Modulation- Limitations

- Turn on delay and resonance frequency are the two major factors that limit the speed of digital laser modulation
  - the photon life time in the laser cavity:

$$\frac{1}{\tau_{ph}} = \frac{c}{n_e}\left(a + \frac{1}{2L}\ln\frac{1}{R_1R_2}\right) = \frac{c}{n_e}g_{th}$$

  - the relaxation oscillation frequency given by:

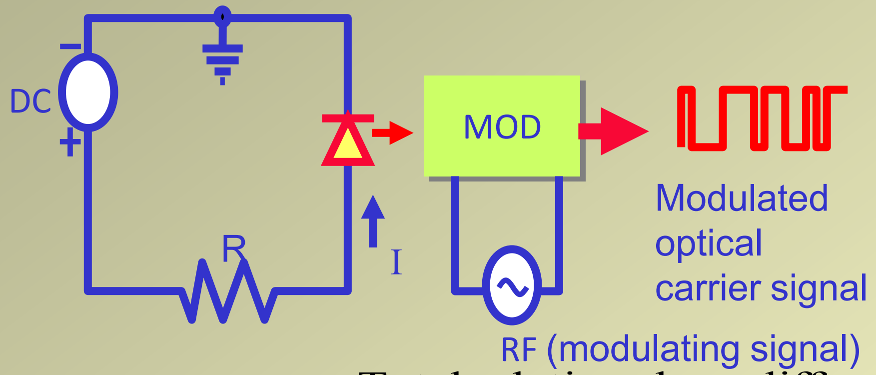
$$f = \frac{1}{2\pi}\frac{1}{\sqrt{\tau_{sp}\tau_{ph}}}\left(\frac{I}{I_{th}} - 1\right)^{1/2}$$

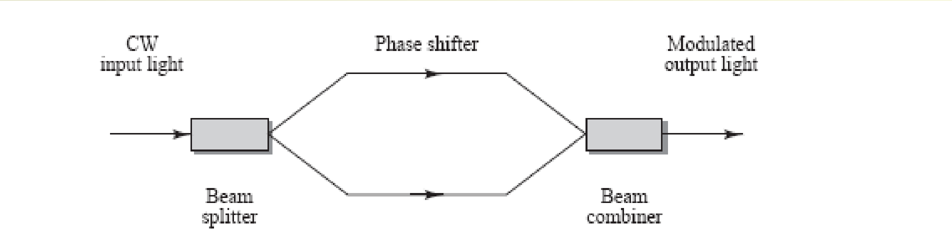


- Saturation and clipping introduces nonlinear distortion with analog modulation (especially in multi carrier systems)
- Nonlinear distortions introduce higher order inter modulation distortions (IMD3, IMD5…)
- Chirp: Unwanted laser output wavelength drift with respect to modulating current that result on widening of the laser output spectrum.

External Modulation

- For high frequencies 2.5 Gbps - 40 Gbps, and is more complex, higher performance.
- AM sidebands (caused by modulation spectrum) dominate linewidth of optical signal





Operational concept of an electro-optical lithium niobate external modulator

- Total relative phase difference between the two interfering signals :

Phase shift in the upper arm output is $\beta\Delta L + m\pi$
Phase shift in the lower arm output is $\beta\Delta L$

If m is even - - > constructive interference (inphase)
If m is odd - - > destructiven interference (opposite phase)
Light intensity modulation will result for all other values of m

LED – Modulation Bandwidth

- The electrical bandwidth:

$$B_{ele} = \frac{\text{Electrical power out at the photodetector}}{\text{Electrical power out in the source}}$$

$$B_{ele} = 10log_{10}\frac{I_{out}^2/R_{out}}{I_{in}^2/R_{in}}$$

The 3 dB bandwidth is when:

$$\frac{I_{out}^2}{I_{in}^2} = 0.5$$

Or

$$\frac{I_{out}}{I_{in}} = \frac{1}{\sqrt{2}} = 0.707$$

LED – Modulation Bandwidth

- The optical bandwidth:

$$B_{opt} = \frac{\text{Optical power out at the photodetector}}{\text{Optical power at the source}}$$

$$B_{opt} = 10log_{10}\frac{I_{out}}{I_{in}}$$

The 3 dB bandwidth is when:

$$\frac{I_{out}}{I_{in}} = 0.5$$

LED – Modulation Bandwidth

- The frequency response of an LED depends on:

  1- Doping level in the active region

  2- Injected carrier lifetime in the recombination region, τ_i.

  3- Parasitic capacitance of the LED

- If the drive current of an LED is modulated at a frequency of ω the output optical power of the device will vary as:

$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}}$$

Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately.

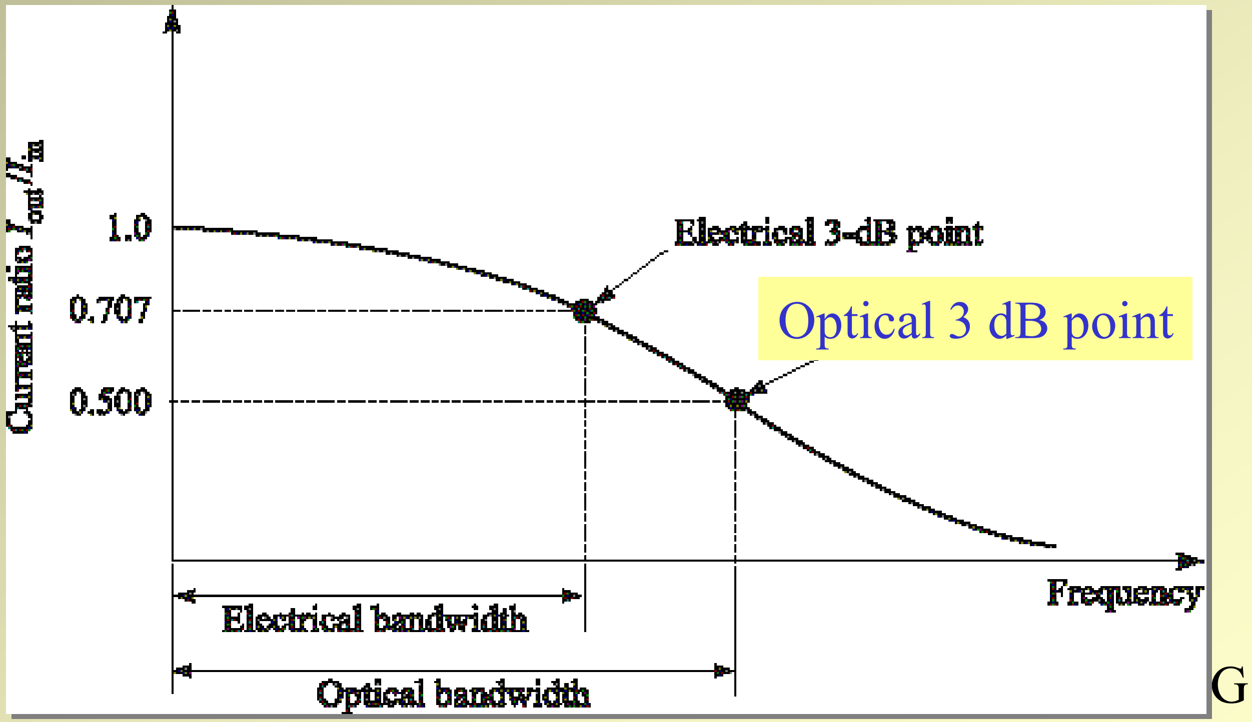
$$\text{Electrical BW} = 10\log\left[\frac{p(\omega)}{p(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right]$$

p : electrical power, I : electrical current

Modulation Bandwidth

Optical Bandwidth B_{opt} - Larger than B_{ele}

$$\text{Optical BW} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right]$$



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Light Source - Nonlinearity

$x(t)$ → Nonlinear function $y=f(x)$ → $y(t)$

$$x(t) = A\cos\omega t$$

$$y(t) = A_0 + A_1\cos\omega t + A_2\cos 2\omega t + \ldots$$

Nth order harmonic distortion:

$$20\log\left(\frac{A_n}{A_1}\right)$$

Intermodulation Distortion

$$x(t) = A_1 \cos\omega_1 t + A_2 \cos\omega_2 t \;\Rightarrow$$

$$y(t) = \sum_{m,n} B_{mn} \cos(m\omega_1 + n\omega_2)t \qquad m,n = 0,\pm1,\pm2,\ldots$$

Harmonics:

$$n\omega_1, m\omega_2$$

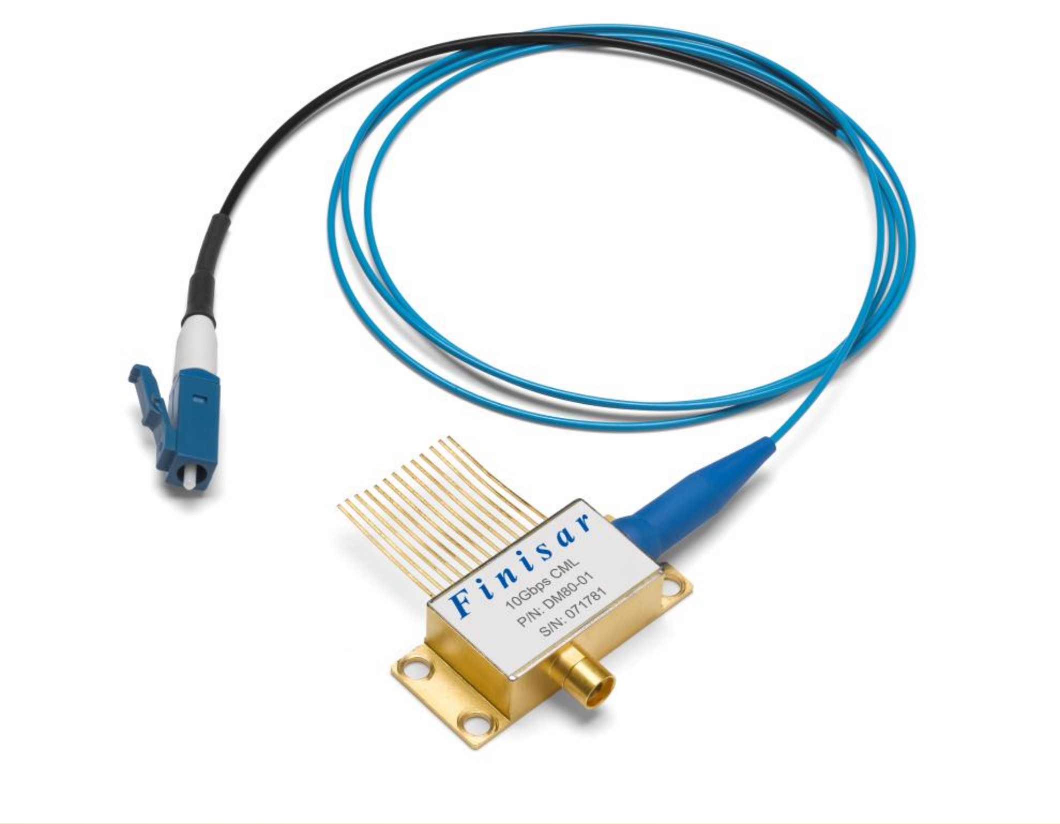
Intermodulated Terms:

$$\omega_1 \pm \omega_2, 2\omega_1 \pm \omega_2, \omega_1 \pm 2\omega_2, \ldots$$

LD – Noise Sources

- **Modal (speckel) Noise**: Fluctuations in the distribution of energy among various modes.
- **Mode partition Noise**: Intensity fluctuations in the longitudinal modes of a laser diode, main source of noise in single mode fiber systems.
- **Reflection Noise**: Light output gets reflected back from the fiber joints into the laser, couples with lasing modes, changing their phase, and generate noise peaks. Isolators & index matching fluids can eliminate these reflections.

LD – Transmitter Package



Final Comments

- Covered two types of light sources
- Drivers circuits
- Modulation
- Bandwidth

- Next Lecturer – **Optical Detectors and Receivers**