Dipartimento INFOCOM
Università degli Studi di
Roma “La Sapienza”

Departamento de Señales y
comunicaciones
ULPGC

Optical Communications

Telecommunication Engineering
School of Engineering
University of Rome La Sapienza
Rome, Italy
2005-2006

Lecture #3, May 4 2006

Emitters

OPTICAL SOURCES

LED (Light Emitting Diodes):

- Produces scattered incoherent light
- Electrically simple to use and control
- Low cost
- Transmission rates up to several hundred of MHz, depending on the emitting window (not for the 1st)

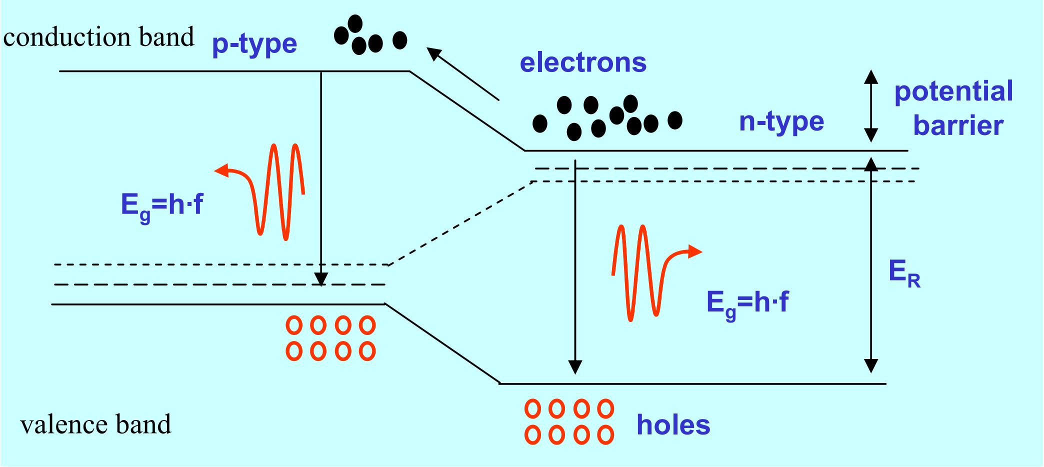
LD (Laser Diodes):

- Produces a narrow beam of coherent light
- Requires more complex control than a LED
- High cost
- Transmission rates up to tens of GHz
- High optical power output available

LIGHT EMISSION ON SEMICONDUCTORS

p-n junction with forward bias
and spontaneous emission

$$h=6{,}62\cdot10^{-34}\ J\cdot sec$$



- In a biased p-n junction minority carriers (forward current) cross the junction
- On the p side empty electron states are occupied by injected electrons from the N side
- On the n side empty hole states are occupied by injected holes from the P side
- Increased concentration of minority carriers in the opposite type region leads to recombination across the bandgap, releasing the bandgap Eg.
- Recombination may be non-radiative (dissipated as heat) or radiative, resulting in a photon of energy Eg

LIGHT EMITTING DIODES (LED OR IRED)

LED: Light Emitting Diode (also known as IRED InfraRed Emitting Diode)

These are **diodes** (current can only flow in one direction) that have very little resistance so large amounts of current will flow through it, unless current is limited by a resistor.

LED CLASSIFICATION

Types of LEDs: white, blue, green, aqua, red, orange, yellow, violet, ultra-violet, and infrared.

Angle: is the width of the beam of light produced by the LED.

Intensity (measured in Milli Candle Power): mci stands for Milli Candle Power and measures the intensity of the LED. Intensity is measured in the most intense portion of the beam.

Driving current: usually about 20 milliamps.

Size: a common package "T-1 3/4" means about 5 mm.

LED CHARACTERISTICS

- Produces scattered incoherent light
- Electrically simple to use and control
- Low cost and reliable
- Transmission rates up to several hundred of Mbits/sec (depending on the emitting window, not the 1^{st}…)

For communications over the fiber also consider that:

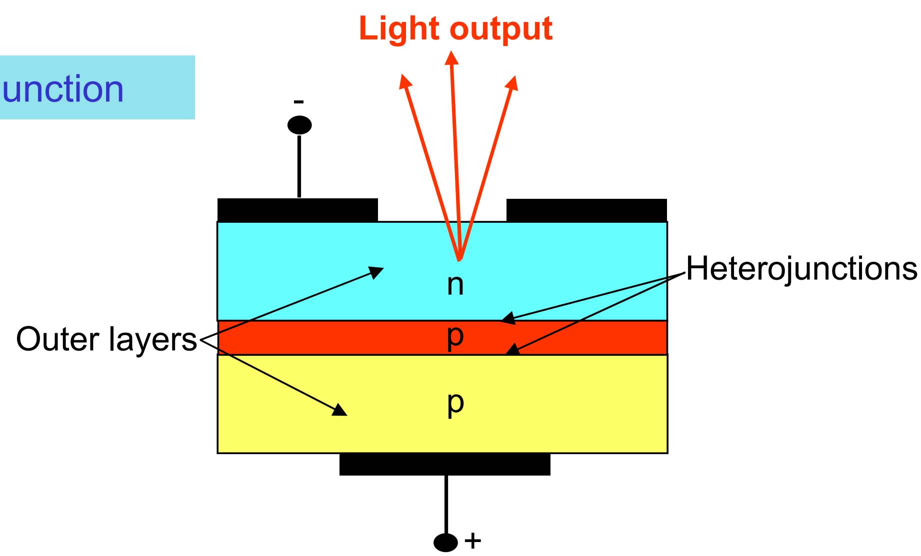
- Coupling sufficient optical power into a fiber is difficult
- Use of LEDs is restricted to large core fibers
- Not suitable for single mode fiber due to the size of the core
- Broad spectral width causes material dispersion

LED STRUCTURE

• The most common structure is the so called Double Heterojunction (DH) or Double Heterostructure

• Heterojunction is an interface between two semiconductive materials of different bandgap energies (as opposed to a so called homojunction)

Double Heterojunction



DH LED OPERATION

• Forward bias electrons are injected through the p-n junction into the p type GaAs layer from the n type AlGaAs layer

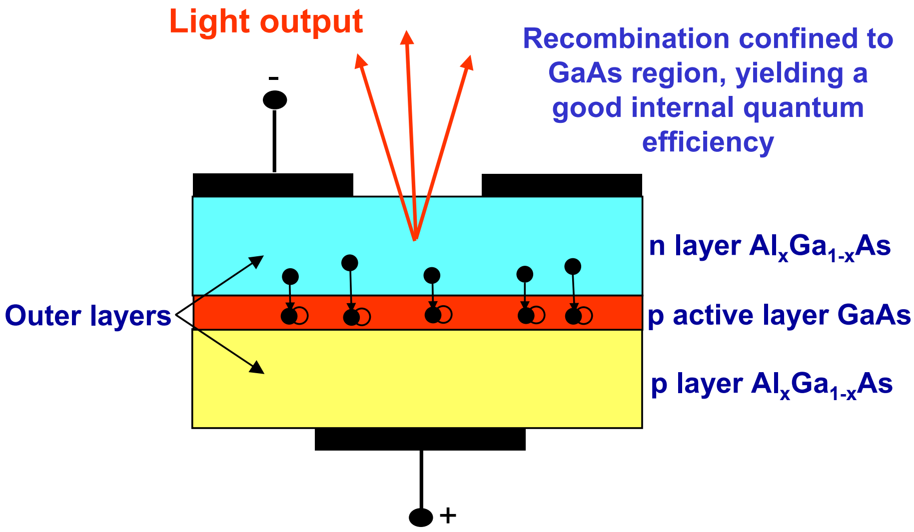
• In the GaAs region these electrons become minority carriers, recombine with holes (majority carriers), and thus release photons. Photon energy corresponds to the bandgap energy of GaAs

• Injected electrons do not pass into p type AlGaAs region, because of the potential barrier at p-p junction

• Higher bandgap energy in the outer layers means absorption is unlikely for photons generated in the active layer

• The outer layers are thus transparent to the photons generated

• Transparency results in low loss in the emission of light



TOTAL OPTICAL POWER GENERATED

- Given the quantum efficiency η that expresses the capability of the device in emitting photons, the rate of emitted photons R_p generated by radiative recombination is as follows:

$$R_p = \eta \frac{i}{q}$$

i is the forward bias current in Ampères
q is the charge on an electron in Coulombs

Quantum efficiency η is actually the result of both internal efficiency η_{int} and external efficiency η_{ext} of the device.

$$\eta_{\text{int}} = \frac{R_{gp}}{R_q} = \frac{R_{gp}}{i/q}$$

Quantum efficiency η is actually the result of both internal efficiency η_{int} and external efficiency η_{ext} of the device. Internal efficiency is the ratio between the number of generated photons per unit time R_{gp} vs. the number of electrons in the bias current per unit time R_q

$$\eta_{\text{ext}} = \frac{R_p}{R_{gp}}$$

External efficiency is the ratio between the number of emitted photons per unit time R_p vs. the number of generated photons per unit time R_{gp}

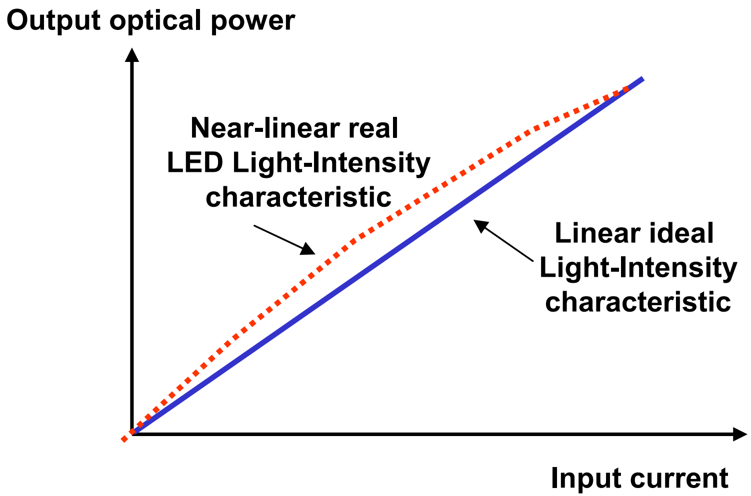
$$P = \eta_{\text{int}}\eta_{\text{ext}} \frac{i}{q} \cdot hf = \eta \frac{i}{q} \cdot \frac{hc}{\lambda}$$

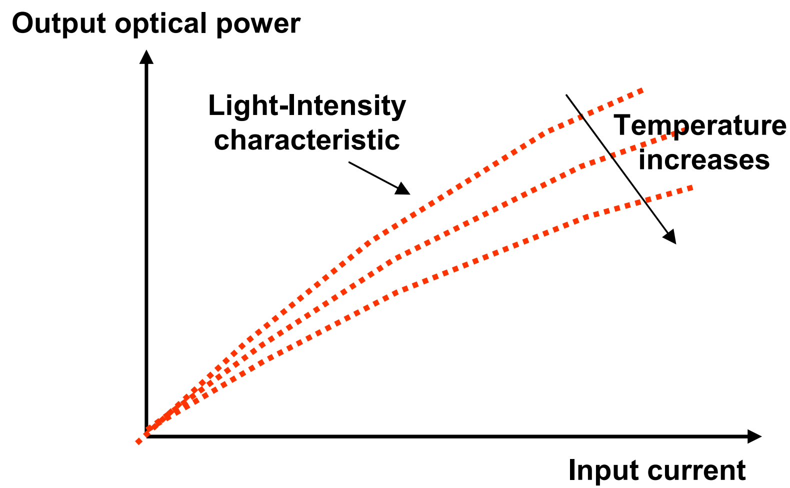
Each photon has an energy *hf* Joules, so the optical power *P* measured in watts emitted by the LED is given by the product of R_p and *hf*

LED CHARACTERISTICS: LINEARITY

LEDs are intrinsically reasonably linear, and are thus suitable for analog transmission systems

The input-output curve is temperature dependent,
For a given current, optical power decreases when temperature increases

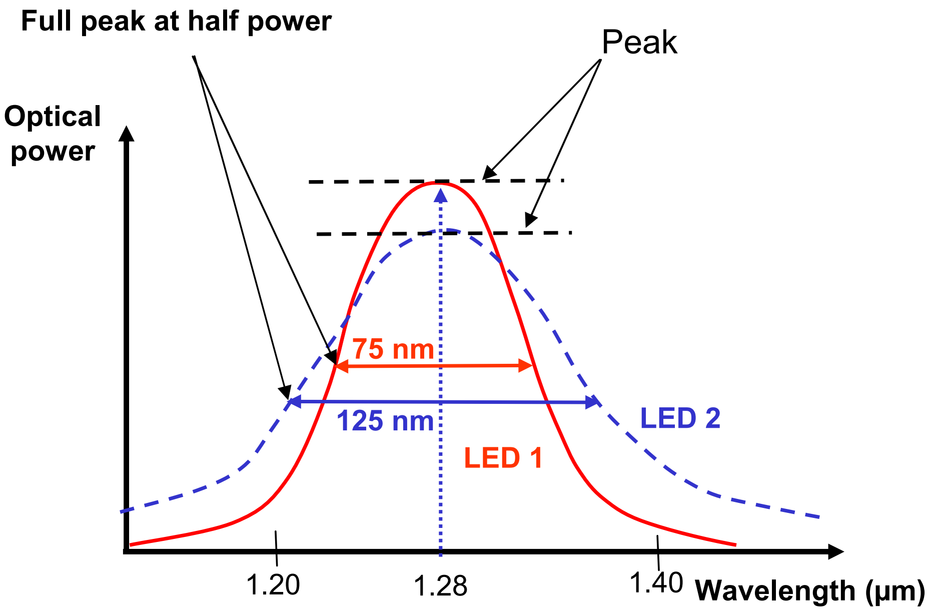




LED CHARACTERISTICS: SPECTRAL RESPONSE

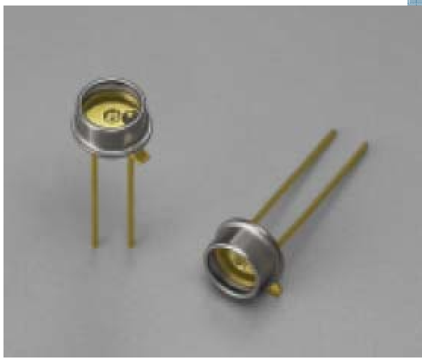
Optical spectra

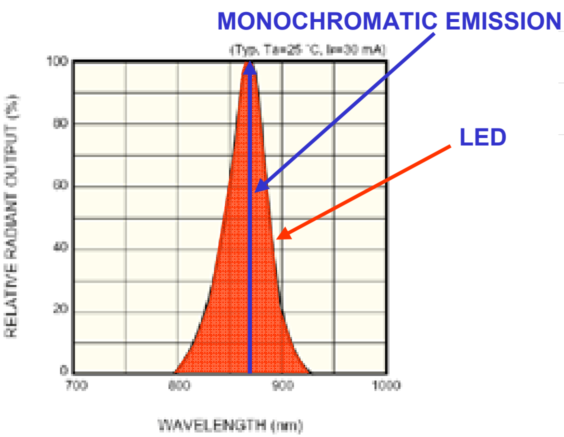
- For LEDs at 800-900 nm the typical spectral width at the half power (3 dB) points is about 25-40 nm.
- In the region 1100 to 1700 nm the spectral width is about 50 to 160 nm
- Output spectra broadens with temperature (0.1 to 0.3 nm per ºC)



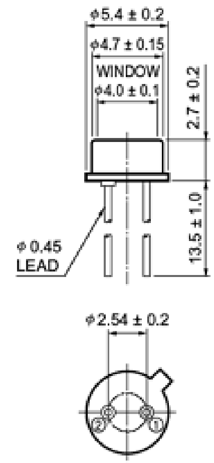
COMMERCIAL LEDs

HAMAMATSU L8013



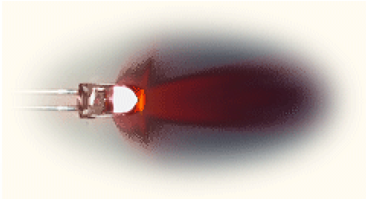


Package	Optical Link Use
Peak emission wavelength min	840 nm
Peak emission wavelength max	900 nm
Peak emission wavelength typical	870 nm
Spectral half width	45 nm
Radiant flux	6.5 mW
Forward voltage	1.45 V
Cut-off frequency	50 MHz

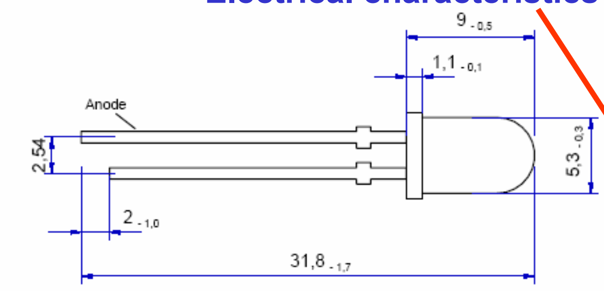


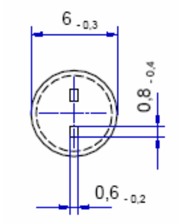
units in mm

COMMERCIAL LEDs



Electrical characteristics





Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test Conditions	Symbol	Value	Unit
Forward current (DC)		I_F	100	mA
Peak forward current	($t_P \leq 50$ µs, $t_P/T = 1/2$)	I_{FM}	200	mA
Surge forward current	($t_P \leq 10$ µs)	I_{FSM}	2000	mA
Operating temperature range		T_{amb}	-20 to +100	°C
Storage temperature range		T_{stg}	-55 to +100	°C
Weight			0.33	g

Optical characteristics

Optical and Electrical Characteristics

T_{amb} = 25°C, unless otherwise specified

Parameter	Test Conditions	Symbol	Min	Typ	Max	Unit
Forward voltage	I_F = 100 mA	V_F		1.8	2.1	V
Radiant power	I_F = 100 mA	Φ_e		28		mW
Peak wavelength	I_F = 100 mA	λ_p		810		nm
Spectral bandwidth at 50%	I_F = 100 mA	$\Delta\lambda_{0.5}$		35		nm
Viewing angle		φ		20		deg.
Switching time	I_F = 100 mA	t_r, t_f		40		ns

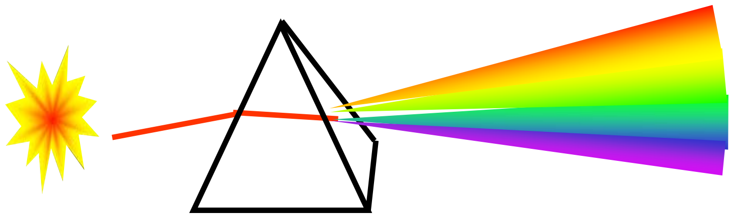
Roithner ELD-810-525

Semiconductor: AlGaAs/AlGaAs
Package: 5 mm plastic lens
Description: High-power, high-speed for optical communications

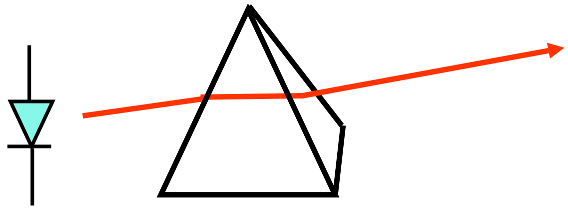
LASER FUNDAMENTALS

Monochromaticity and wavelength, or color, are related. White light, like light from the sun or a light bulb, is composed of all colors. A laser lases only in a very small portion of the spectrum. We speak of red lasers or green lasers or blue lasers but not white light lasers.

The **intensity**, indicates how much light is present. Although the total amount of energy emitted by the sun is much greater than the energy emitted by a laser, in the narrow spectral region (color band) in which the laser lases, the laser's output energy far exceeds that of the sun or any other known source.



White light through a prism



Laser beam
through a prism

LASER FUNDAMENTALS

Laser efficiency

- Internal laser quantum efficiency η_{int} is defined as for LEDs and represents the ratio between the number of generated photons per unit time R_{gp} vs. the number of electrons in the bias current per unit time R_q

$$\eta_{\text{int}} = \frac{R_{gp}}{R_q} = \frac{R_{gp}}{i/q}$$

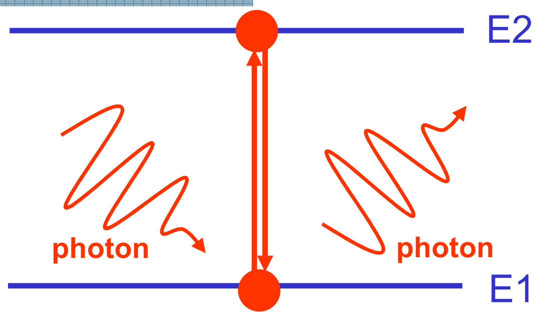
- External efficiency is as in LEDs the ratio between the number of emitted photons per unit time R_p vs. the number of generated photons in the resonating cavity per unit time R_{gp}

$$\eta_{\text{ext}} = \frac{R_p}{R_{gp}}$$

- Laser efficiency is the resulting product of η_{int} and η_{ext}, and is therefore a differential efficiency that is expressed by:

$$\eta = \eta_{\text{int}}\eta_{\text{ext}} = \frac{R_p}{i/q}$$

LASER FUNDAMENTALS



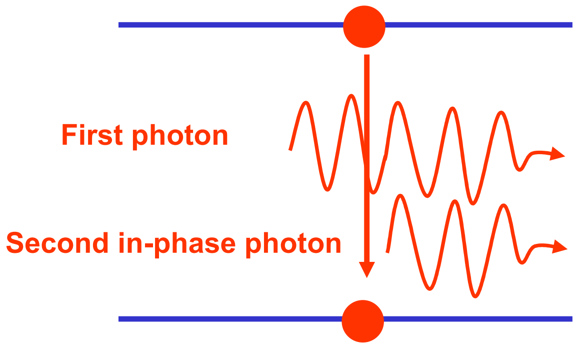
- **Spontaneous emission:** one electron makes a transition from a high energy state E2 to a lower energy state E1, resulting in the emission of a photon

$$E = E_2 - E_1 = hf$$

- **Stimulated emission:** a photon, with an energy equal to E2-E1 interacts with an atom in the upper energy state, causing an electron in the atom to jump down in the lower state causing the emission of a second photon

    - the second photon has the same phase, frequency of the first

    - this stimulated emission gives the laser its special properties such as narrow spectral width and coherent output radiation



LASER COHERENCE

Directionality and coherence. Normal light sources, such as a flashlight, a light bulb, or the sun, emit energy in all directions. A laser, on the contrary, emits light only in a very well defined direction and all photons are in-phase (a property called **coherence)**.

↓

The coherence of the stimulated emission means that:

- emitted photons are **in phase** with the incident photon
- emitted photons have same **wavelength** as the incident photon
- emitted photons travel in the **same direction** as incident photon

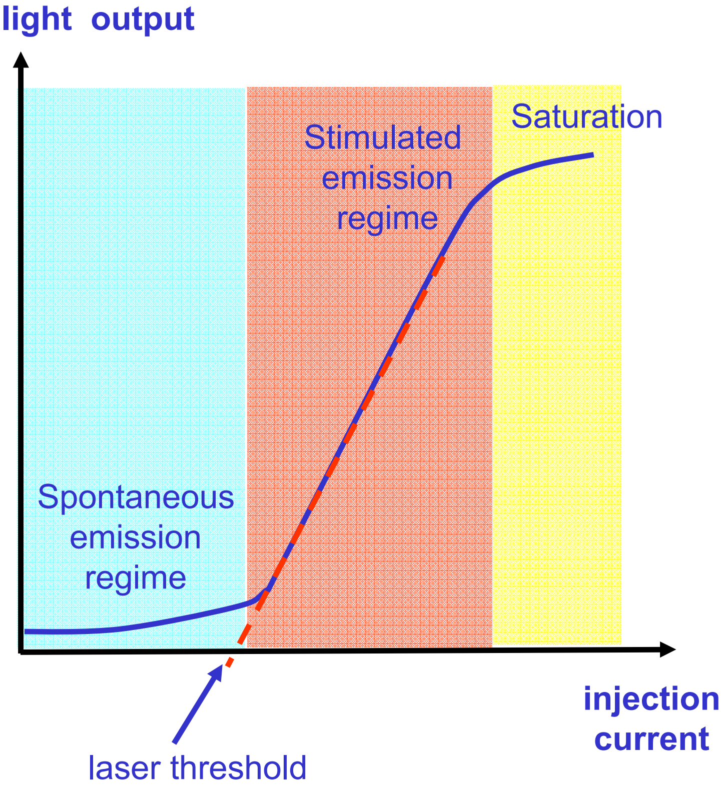
LASER CHARACTERISTICS: THRESHOLD

- All semiconductor laser diodes have a light current characteristic, with a defined threshold current

- Below the threshold spontaneous emission dominates

- Beyond the threshold, where stimulated emission dominates, the differential quantum efficiency increases dramatically

- The threshold current by convention is the intercept on the current axis of a line drawn along the characteristic, as shown on figure



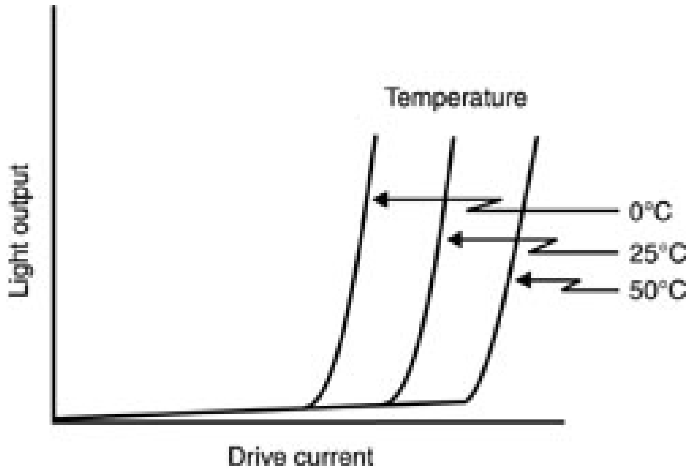
TEMPERATURE DEPENDENCE

The threshold current is highly temperature dependent

The threshold current depends on temperature in an exponential fashion, according to the equation:

$$I_t(T_2) = I_t(T_1)\cdot\exp[(T_2 - T_1)/T_0]$$

where $I_t(T_2)$ and $I_t(T_1)$ are the threshold currents at temperatures T_1 and T_2 respectively, and T_0 is a scale factor with a typical value around 150 ºK.



Example:

if T_1=0 °C and T_2=30 °C, the threshold current will be about 22% higher at the higher temperature.

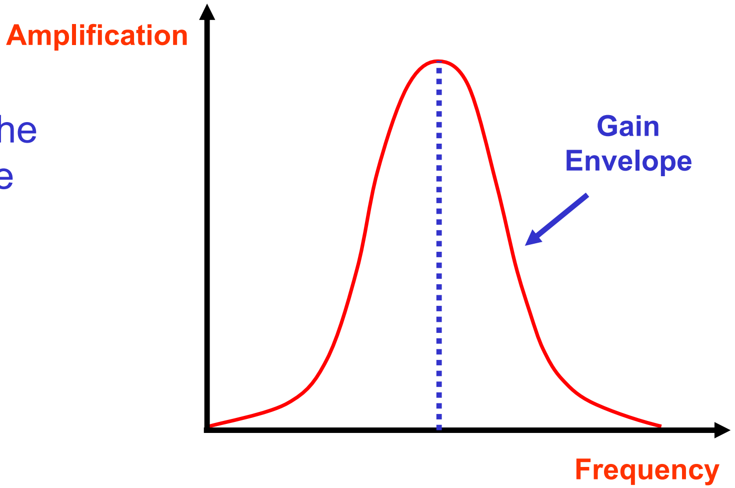
LASING ACTION AND FREQUENCY

- When the saturation point is reached the optical output of the laser is constant

- Saturation is reached when the gain in the medium exactly equals the losses in the medium (such as absorption etc.)

- Gain only occurs over a narrow range of frequencies, centered on the stimulated transition energy $E_t = E2\text{-}E1$, also called the broadened laser transition

Broadening of the gain is originated by the variation around the average value in the transition energy



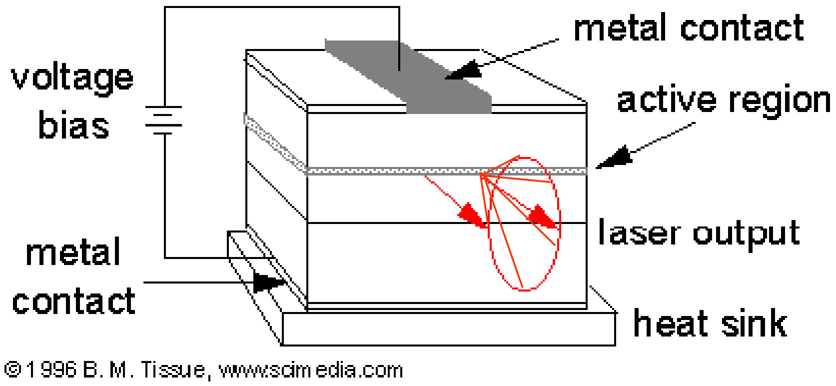
SEMICONDUCTOR LASERS: BASICS

Semiconductor lasers are light-emitting diodes within a resonator cavity that is formed either on the surfaces of the diode or externally.

An electric current passing through the diode produces light emission when electrons and holes recombine at the p-n junction. When the width w and size l of the active medium is small, the conical beam is characterized by a high angular divergences ψ_1 and ψ_2 according to the law

$$\psi_1 = \frac{\lambda}{w} \quad \psi_2 = \frac{\lambda}{l}$$

Special optics must be used to produce a good beam shape.



Schematic of a semiconductor diode laser

These lasers are used in optical-fiber communications, CD players, and in high-resolution molecular spectroscopy in the near-infrared.

Diode lasers are tunable over a narrow range of wavelengths and different semiconductor materials are used to make lasers at **680, 800, 1300,** and **1500 nm**

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SEMICONDUCTOR LASERS: MATERIALS

Material	Wavelength Range (nm)
$Al_{1-x}Ga_xAs$	780-880
$In_{1-x}Ga_xAs_{1-y}P_y$	1150-1650
$Al_xGa_yIn_{1-x-y}P$	630-680

Most semiconductor laser materials are composed of the so-called III-V compounds, (formed by elements from columns III and V of the periodic table)

The original semiconductor lasers were made of crystals containing a junction between p- and n-type gallium arsenide. Nowadays lasers are made using three or four elements from columns III and V of the periodic table (ternary or quaternary compound semiconductors, respectively).

Examples:

$Al_{1-x}Ga_xAs$ (aluminum gallium arsenide),
$In_{1-x}Ga_xAs_{1-y}P_y$ (indium gallium arsenide phosphide)

In this notation, the parameters *x* and *y* are composition parameters that may take values in the range [0, 1]. Thus the $Al_{1-x}Ga_xAs$ system can vary continuously from AlAs ($x = 0$) to GaAs ($x = 1$).

LASER CLASSIFICATION

- **Class 1:**
  - Very low power, always safe
- **Class 2:**
  - Visible part of the spectrum [400nm,700nm]
  - Maximum power 1mW (for continuous wave)
  - Easy preventions for safety (glasses)
- **Class 3A:**
  - Visible part of the spectrum [400nm,700nm]
  - Maximum power 5mW (for continuous wave)
  - Risk when direct view (even with glasses)

LASER CLASSIFICATION

- **Class 3B:**
  - Valid for all wavelengths [200 nm,1mm]
  - Maximum power of 500 mW
  - Risk for direct or reflected vision (even with glasses)
  - Risk even for incidence over skin
  - More complex safety rules are required

- **Class 4:**
  - Valid for all wavelengths [200 nm,1mm]
  - Power > 500 mW
  - Risk for direct, reflected or scattered vision (even with glasses)
  - High risk even for incidence over skin
  - High complexity safety rules are required (should be confined)

LASER CLASSIFICATION

By their lasing medium

Lasers are often described by the kind of lasing medium they use: gas, liquid, solid, semiconductor, or dye.

By their emission characteristics

Lasers are also often characterized by duration of laser light emission:

- A ***continuous wave (CW)* laser** is a laser which emits a steady beam of light. It is characterized by its power density [W/cm^2]

- A ***pulsed*** laser emits light in an on-off that is pulsed manner. It is characterized by its energy density or radiant exposition [$Joule/cm^2$]

- A ***Q-switched* laser** is a pulsed laser which contains a shutter that does not allow emission of laser light until opened. Energy is built up in a Q-switched laser and released by opening the shutter to produce a single very intense laser pulse.

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LASER DEVICE EXAMPLE

Electrical characteristics

THORLABS

LD L980P010
980nm, 10mW Laser Diode

Optical aperture

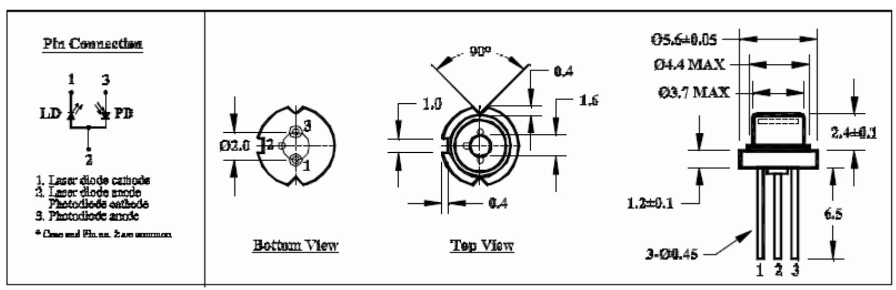
Optical power

OPTICAL AND ELECTRICAL CHARACTERISTICS (Tc=25°C)

DESCRIPTION	MIN.	TYPICAL	MAX.	TEST CONDITION
Lasing Wavelength (nm)	965	980	995	Po=10mW
Threshold Current (mA)	20	25	40	Po=10mW
Operation Current (mA)	30	45	60	Po=10mW
Operation Voltage (V)	2.0	2.2	2.7	Po=10mW
Monitor Current (μA)	10	-	90	Po=10mW, VR=5V
Slope Efficiency (mW/mA)	0.3	0.4	0.7	***
Beam Divergence ¦ (°)	8	10	11	Po=10mW
Beam Divergence ? (°)	25	31	40	Po=10mW
Astigmatism (μm)	***	11	***	Po=10mW, NA=0.4

ABSOLUTE MAXIMUM RATINGS (Tc=25°C)

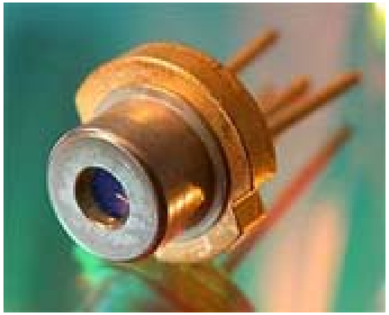
DESCRIPTION	SYMBOL	RATED VALUE
Optical Power (mW)	Po	10
Operation Temperature (°C)	Top	-10 to +50
Storage Temperature (°C)	Tstg	-40 to +85
LD Reverse Voltage (V)	VLDR	2
PD Reverse Voltage (V)	VPDR	30



LASER DEVICE EXAMPLE

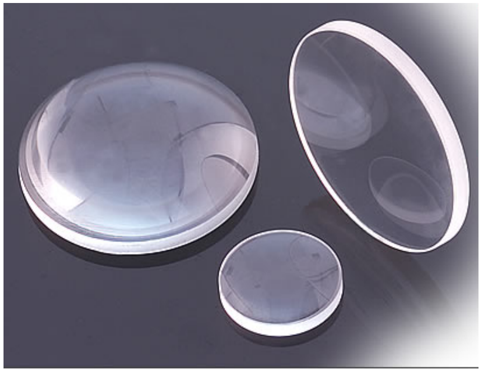
ROITHNER RLT8710MG
High Power Infrared Laserdiode

Lasing wavelength: 870 nm typ.
Output power: 10 mW cw
Package: 5.6 mm, TO-18



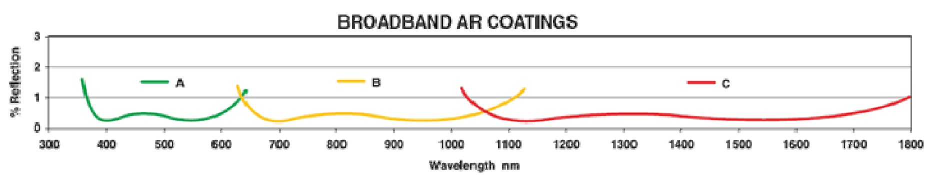
SOURCE: http://www.roithner-laser.com/

LENSES AT THE EMITTER



Plano-Convex optics This lens shape is used for focusing collimated light or for collimating a point source.

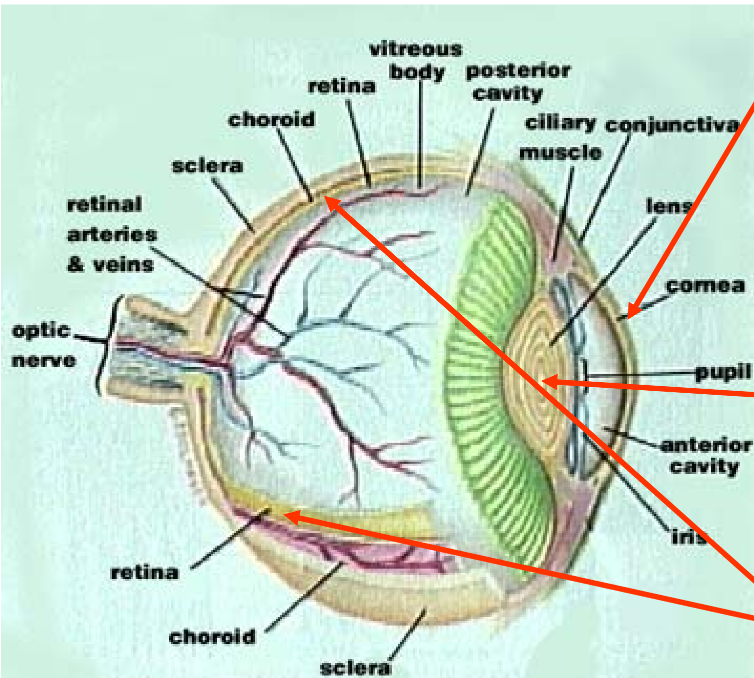
Wavelength Range: 350nm to 2µm
Focal Lengths from 10mm to 1000mm
Diameters from 6mm to 75mm
Three Standard Anti-Reflection Coating Ranges



A-Coating: 350-650nm B-Coating: 650-1050nm C-Coating:1050-1620nm

SAFETY CONSIDERATIONS FOR IR EMTTERS

The three parts of the eye of concern in laser injuries are the *cornea*, *lens* and *retina*:



The *cornea* is the transparent layer of tissue covering the surface of the eye. The cells on the surface of the cornea have a lifetime of only about 48 hours, therefore cell turnover is quite fast. Injury to cells on the surface of the cornea is generally repaired quickly, but injury to deeper layers of the cornea can result in permanent change to the cornea.

The *lens* of the eye focuses light to form images in the eye. Damage to the lens can cause the destructive interference of light within the lens, resulting in a "milky" area or cataract.

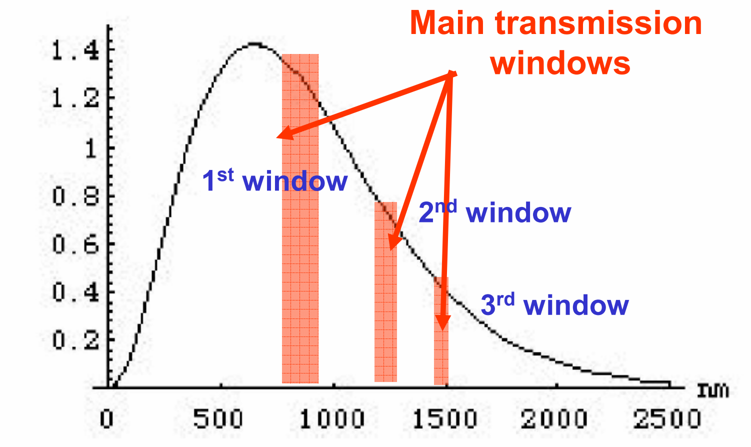
The *retina* is made up of layers of nerve cells and is used for reception of the light in the eye. Damage to cells in the retina can result in loss of vision

LASER BEAM HAZARD

Damage to the eyes and skin is of most concern in laser accidents.

Thermal effects are the major cause of tissue damage by lasers. Energy from the laser is absorbed by the tissue in the form of heat, which can cause localized, intense heating of sensitive tissues. The amount of thermal damage that can be caused to tissue varies depending on the thermal sensitivity of the type of tissue. Thermal effects can range from erythema (reddening of the skin) to burning of the tissue. Factors that affect thermal damage to tissue are:

- Amount of tissue affected
- Wavelength of light
- Energy of the beam
- Length of time that the tissue is irradiated



Human eye response (as a function of wavelength)

LASER RISK CLASSIFICATION

Class	Charateristics	Damage	Risk
I	Power is limited to a maximum	None	None
II	Power is limited to a maximum, only exposition for Visible beam for periods of time superior to 0.25 s	Eye	Chronical damage if time is superior to 1000s
IIIa	Damages if it is focused directly to the eye	Eye	Chronical damage if time is superior to 0.25s
IIIb	Damages if focused directly or reflected into the eye or the skin	Eye Skin	Severe and permanent damage
IV	Damages if focused directly, reflected or scattered into the eye or the skin	Eye Skin	Severe and permanent damage

Not used on wireless communications

FURTHER READING

comprehensive tutorials on optical emitters can be found in several url directions, e.g.

http://repairfaq.ece.drexel.edu/sam/CORD/leot/

Other sources about optical emitters can be found at some manufacturer´s pages:

http://www.hamamatsu.com
http://www.thorlabs.com

Esempio di un laser di classe 4 utilizzato a mo' di radar per indagini atmosferiche (LIDAR)

- Laser ad impulsi
- Ogni impulso dura circa 10 nsec e porta con se 100 mJoules
- La frequenza di ripetizione degli impulsi è di 10 Hz ovvero 1 impulso ogni 100 msec
- Quindi la potenza di "picco" è di 10^7 watts, ovvero 10 Mwatts
- La potenza media è di 1 watt