ELEC4705 – Fall 2009

Tom Smy

LECTURE 18
Optical Systems (Lasers and Detectors)

Contents

18.1. Signal regeneration - optical amplifiers

In any atom or solid, the state of the electrons can change by:

(a) Stimulated absorption:
in the presence of a light wave, a photon is absorbed, the electron is excited to a higher energy level.

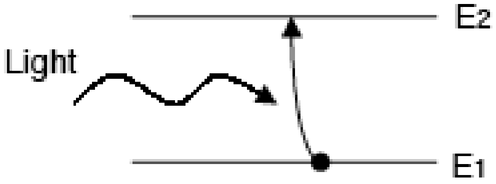


Figure 1. Stimulated absorption

(b) Stimulated emission:
In the presence of a light wave, a photon is emitted, the electron drops too a lower energy level.

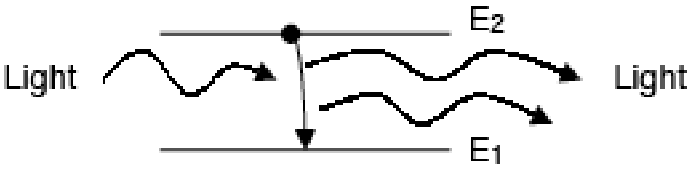


Figure 2. Stimulated emission

(c) Spontaneous emission:
In the absence of light, a photon is emitted and the electron drops to a lower energy level.

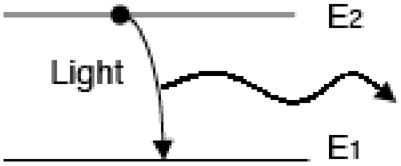


Figure 3. Spontaneous emission

NOTE: For stimulated processes , the absorbed or emitted photon has exactly the same phase f and frequency w (or wavelength l) as the stimulating light (coherence).

Stimulated processes (emission and absorption) are proportional to the light intensity at the appropriate frequency.

(a) Stimulated absorption rate:
$r_{12(stim)} = B \cdot I(w)$
(b) Stimulated emission rate:
$r_{21(stim)} = B \cdot I(w)$
(c) Spontaneous emission rate:
$r_{21(apon)} = A$

Where A and B are the Einstein coefficients. These rates determine the probability that a particular electron will undergo stimulated (or spontaneous) emission within a given time interval.

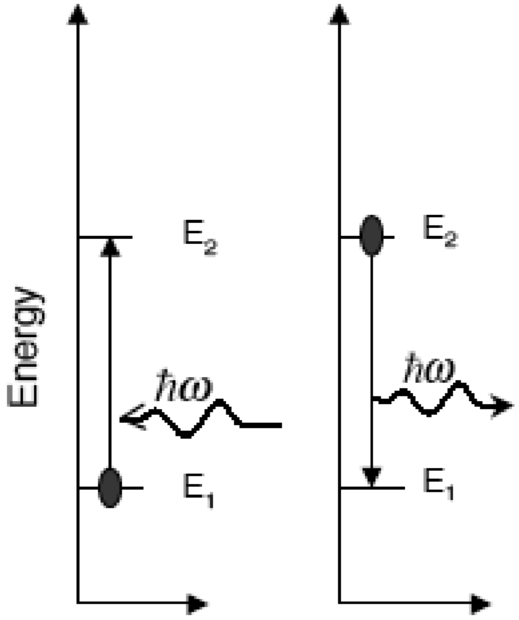


Figure 4. Emission/ Absorption

How does the intensity $I(w)$ of a light wave change when passing through a medium with $n_1$atoms in the ground state and n_2 atoms in the excited state?

$$\frac{\partial I(w)}{\partial x} \sim \hbar w(n_2 r_{21} - n_1 r_{12}) = \hbar w(n_2 - n_1) \cdot B \cdot I(w) \qquad (18.1)$$

$$\frac{\partial I(w)}{\partial x} = I_0 e^{-\alpha x} \tag{18.2}$$

The absorption/gain coefficient α depends on the number of atoms in the excited n_2 and ground states n_1 as $\alpha \sim \hbar w(n_2 - n_1) \cdot B$

- Equilibrium ($n_1 > n_2$ (α positive)) i.e. **Absorption**
- Population Inversion ($n_1 < n_2$ (α negative)) i.e. **Gain**
  Need to *"pump"* electrons to n_2 from n_1.

18.1.1. Erbium doped optical amplifier (EDFA)

Fundamental to all rare-earth-doped amplifier systems is the ability to invert the population of ions from ground state to an excited state. The excited state acts as a storage of pump power from which incoming signals may stimulate emission.

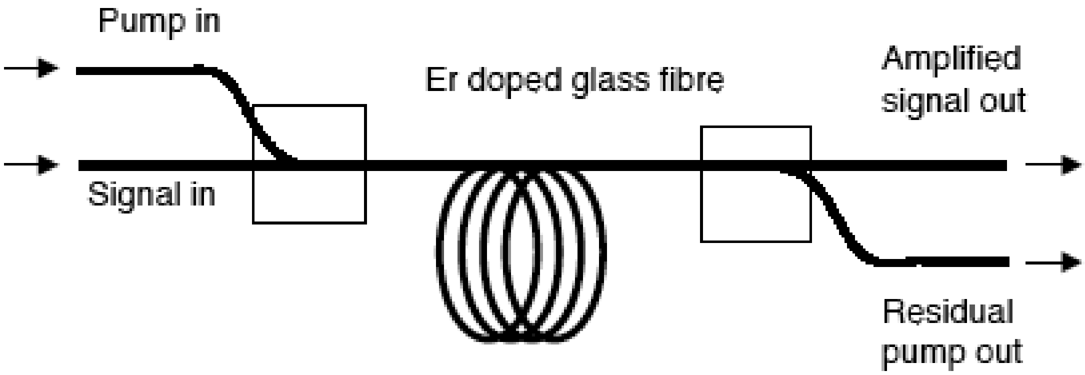


Figure 5. EDFA

Pump: high power light beam at $\lambda = 980\, or\, 1480\, nm$.
Signal: Telecomm signal on a $\lambda = 1530 - 1565 - 1480\, nm$ light beam.

Gain $\sim 40\, dB$ for 50 meters of EDFA fiber
Gain > 0 for $\lambda = 1530 - 1565\, nm$

18.1.2. Energy levels of Er in a Silica Fiber

Each level consists of many closely spaced sublevels. Wavelength on the right indicate the spectral region associated with each transition.

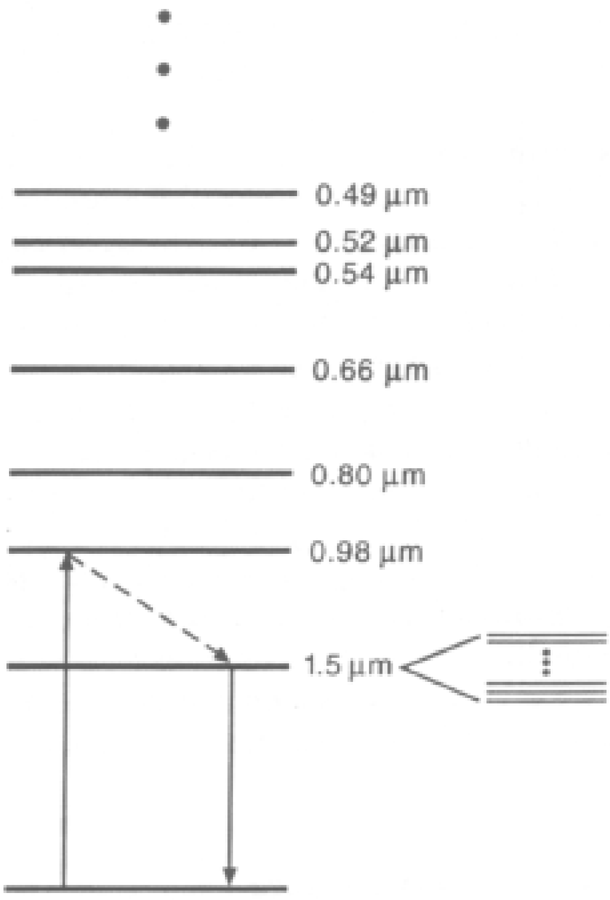


Figure 6. Energy Levels

18.2. Optical signal source: Laser Light Amplification by Stimulated Emission of Radiation

Source must have:

narrow frequency (wavelength) linewidth: to avoid dispersion effects since speed of light depends on wavelength.

coherence (phase and wavelength are constant): for efficient coupling into a single mode optical fibre, and well defined signal modulation.

Signal source should be a laser for high speed long distance communications.

To get laser action we need:

(a) An active medium which emits radiation at the required frequency.
(b) A population inversion must be created within the medium.
(c) Optical feedback at the ends of the medium to form a resonant cavity.

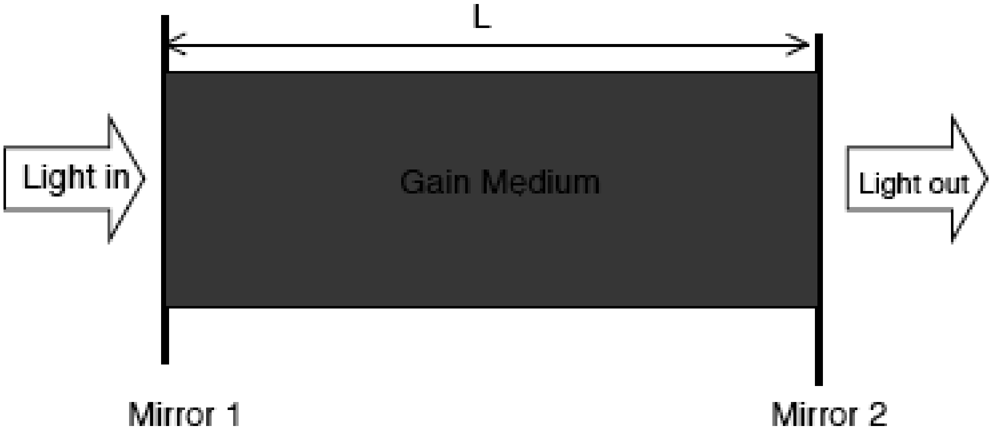


Figure 7. Add Mirrors To Amplifier

Note that satisfying the first two conditions can provide light amplification but not the highly collimated, monochromatic (additional frequency selectivity provided by mirrors) beam of light. Initially light is stimulated in all directions, the mirrors provide selectivity since only those photons perpendicular to the mirrors will stay inside the resonator.

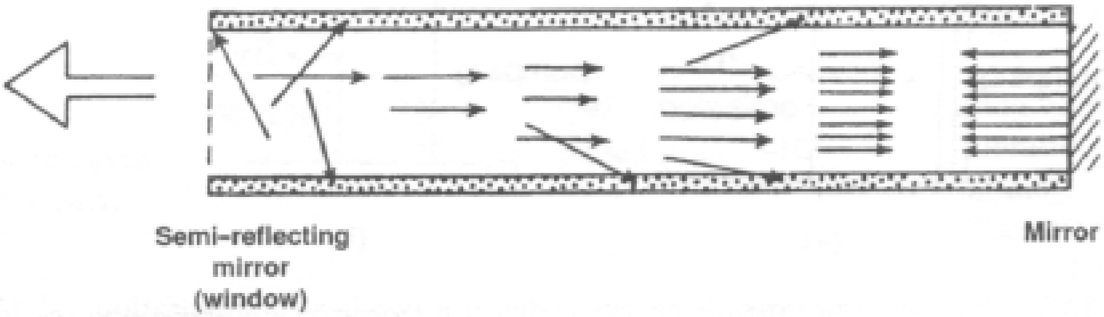


Figure 8. Light through mirrors

18.2.1. Laser Operation: Threshold conditions (minimum gain requirements)

In the active medium some of the photons get absorbed (other transitions than the desired ones) or scattered. To account for this, we introduce the effective loss coefficient γ which reduces the effective gain to $(\alpha - \gamma)$. In traveling from $M_1$to M_2 the beam intensity increases from I_0 to I. After reflection at M_2, the intensity will be R_2 and after a complete round trip the gain G is:

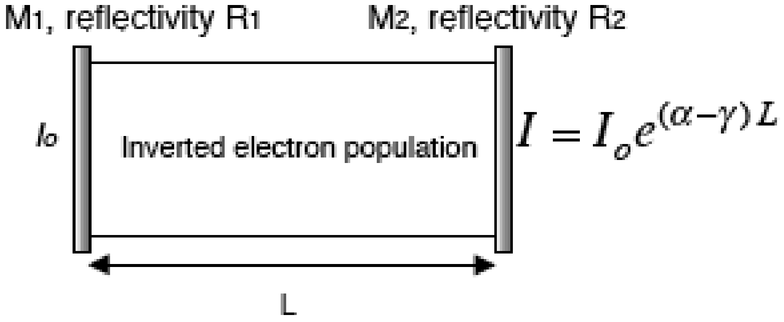


Figure 9. Laser Operation

$$G = \frac{Final\ Intensity}{Initial\ Intensity} = \frac{R_1 R_2 I_0 e^{(\alpha-\gamma)2L}}{I_0} \tag{18.3}$$

- if $G > 1$ a disturbance will undergo net amplification and oscillate
- if $G < 1$ the oscillation will die out. Therefore, we can write the threshold condition as $G = 1$ and from there obtain:

$$\alpha_{th} = \gamma + \frac{1}{2L}\ln(\frac{1}{R_1 R_2}) \tag{18.4}$$

18.2.2. Modes – Waveguide (transverse) modes and Longitudinal modes

18.2.2.1. *Waveguide modes.* A laser can be though of as a waveguide with gain and feedback. As such it has a cross-sectional mode structure like a fiber. These modes must satisfy the boundary conditions for the electric field on the laser walls. A laser can thus be single or multi-mode depending on the frequency of operation.

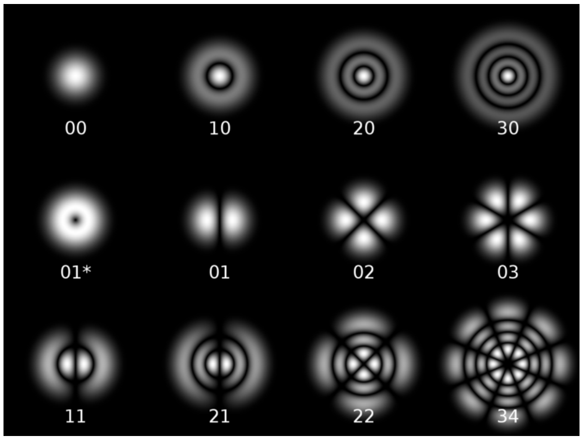


Figure 10. Transverse laser modes

18.2.2.2. *Longitudinal Modes – Frequency selection.* Mirrors at the end also impose boundary conditions on the electric field and impose a mode structure. We must have $L = n \cdot \lambda$ along the laser length as the electric field must go to zero at the ends. This selects the actual frequency of operation of the laser.

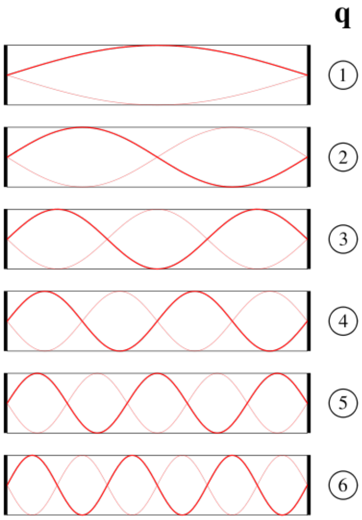
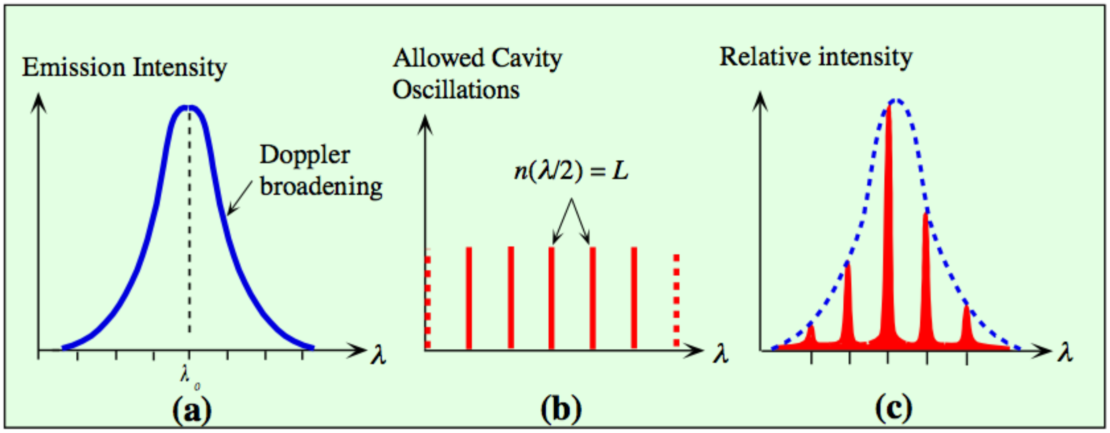


Figure 11. Transverse laser modes

The gain of a laser is frequency dependant due to temperature effects. This means that there is a broadening of the gain around the λ

specified by the band gap/energy levels of the material. The longitudinal mode select the frequency of the light - if the laser is short the allowed frequencies will be well separated and the laser will be single mode.



(a) Doppler broadened emission vs. wavelength characteristics of the lasing medium. (b) Allowed oscillations and their wavelengths within the optical cavity. (c) The output spectrum is determined by satisfying (a) and (b) simultaneously.

Figure 12. Laser Frequency Selection

18.2.3. Lasers for telecommunications

- Properties of semiconductor lasers:
  - small
  - efficient
  - electrically driven and can be electrically modulated
  - can be designed to lase at single specified wavelength
- A semiconductor laser operating between $\lambda = 1530\ and1565\ nm$ is required (i.e. the EDFA band and minimum fiber attenuation)
- Band gap energy $\sim 0.8\,ev \implies$ InGaAsP lasers grown on InP substrates.

18.2.4. Semiconductor Lasers - PN diode

The heart of a semiconductor laser is the p-n junction. A p-n junction provides the active medium, thus we only need to meet the requirements of population inversion and optical feedback.

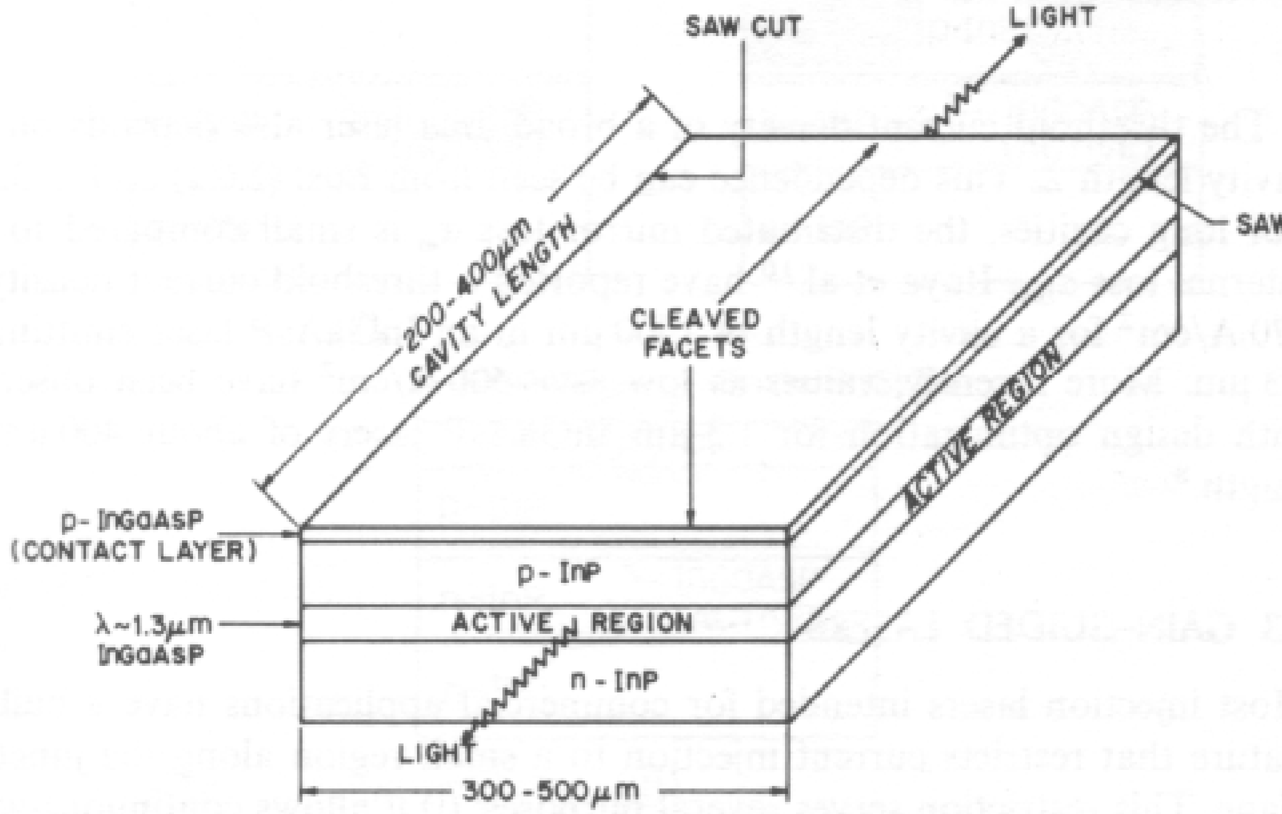


Figure 13. PN Diode Laser

Gain: Stimulated electron and hole recombination at a p-n or p-i-n junction where a *population inversion* is created.

Mirrors: Provided by the cleaved facets of the semiconductor chip, or fabricated gratings.

Wavelength: Photon energy approximately equal to the semiconductor band gap energy]

To obtain stimulated emission, there must be a region of the device where there are many excited electrons and holes present together.

This is achieved by forward biasing a junction formed from very heavily doped n and p materials. In such n-type material, the Fermi level lies within the conduction band. Similarly, for the p-type material the Fermi level lies in the valence band. When the junction is forward biased (V_f), electrons and holes are injected across the junction in sufficient numbers to create a population inversion in a narrow zone called the active region (junction). If the injected carrier concentration becomes large enough, the stimulated emission can exceed the absorption so that optical gain can be achieved in the active region. Laser oscillations occur when the round trip gain exceeds the total losses over the same distance as described before.

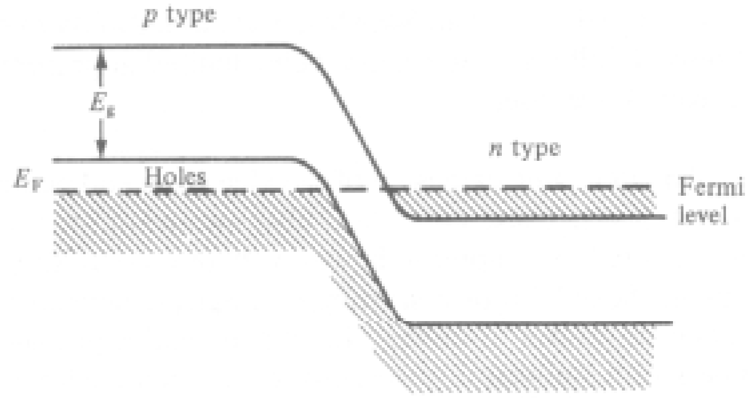


Figure 14. Equilibrium energy band diagram

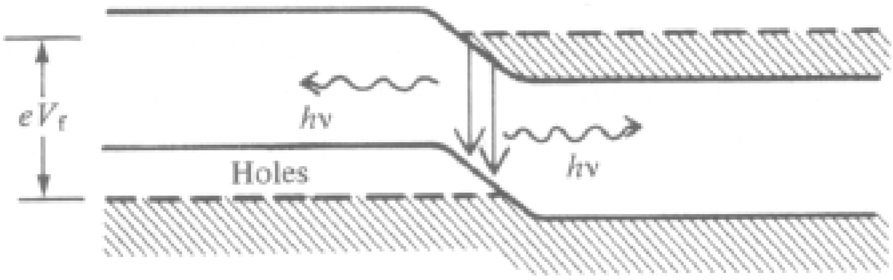


Figure 15. Forward Bias energy band diagram

There are a number of problems:

- Light is not confined to active region (lose power)
- Region of population inversion is not confined.

Need very high current density to achieve lasing

The original semiconductor laser (1962) operated in this way and power dissipation is high therefore it got hot and can only run in a pulsed mode.

18.2.5. $L - I$ curve

A typical $L - I$ (light output power vs. current) curve of an ideal semiconductor laser looks as shown in figure 16. The form of the L-I curve is typical for any laser. When the applied current is below threshold, the output mainly consists of spontaneous emission and Its magnitude is small. When the current exceeds the threshold value, stimulated emission begins to dominate and the output power increases linearly with the applied current.

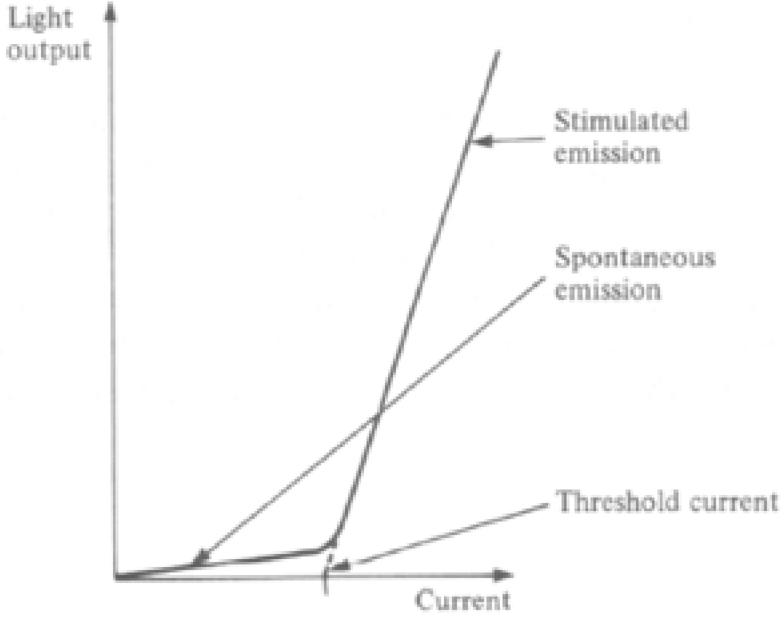


Figure 16. $L - I$ curve

18.2.6. A better laser using bandgap engineering

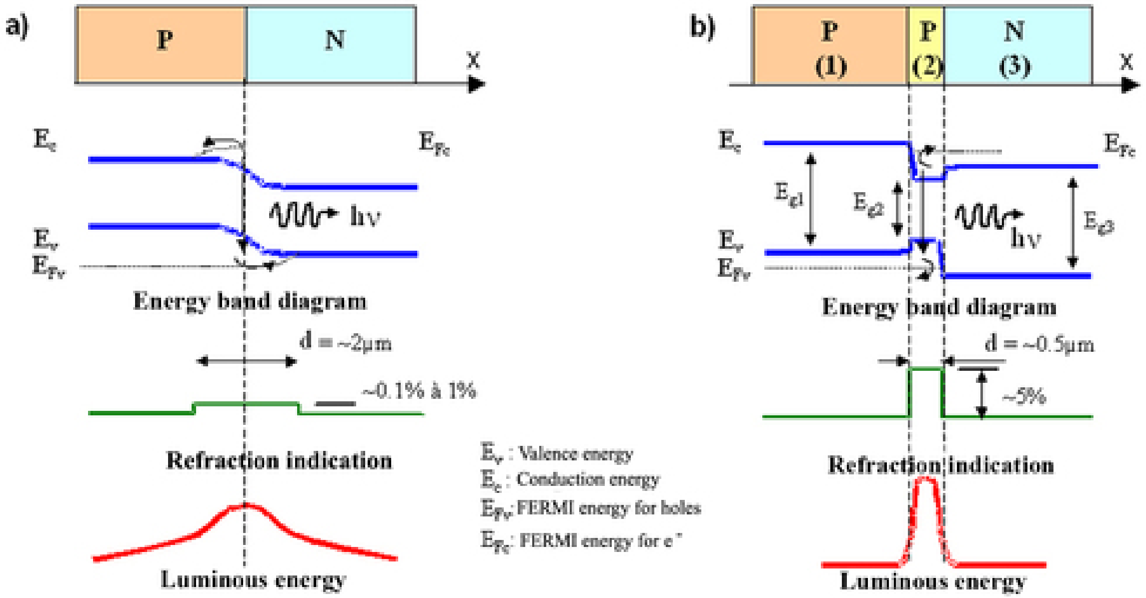


Figure 17. Laser Structures a) homojunction b) Hetrojunction

Use III-V material base and very good control over material deposition. We can achieve:

(a) Carrier confinement due to band structure "notches".
(b) Waveguide action due to index of active region being higher then "cladding".
(c) Much higher stimulated emission rates and optical confinement
(d) Lower threshold currents and heat production.

.

Actual laser is a 3D structure:

(a) Use a contact strip or mesa structure to confine the light to strip.
(b) Periodic index variation (corrugations) to control optical wavelength by creating a Bragg diffraction grating eithe as mirros or as n inplace optical filter.
(c) Use quantum well structures to create more efficient laser structures.

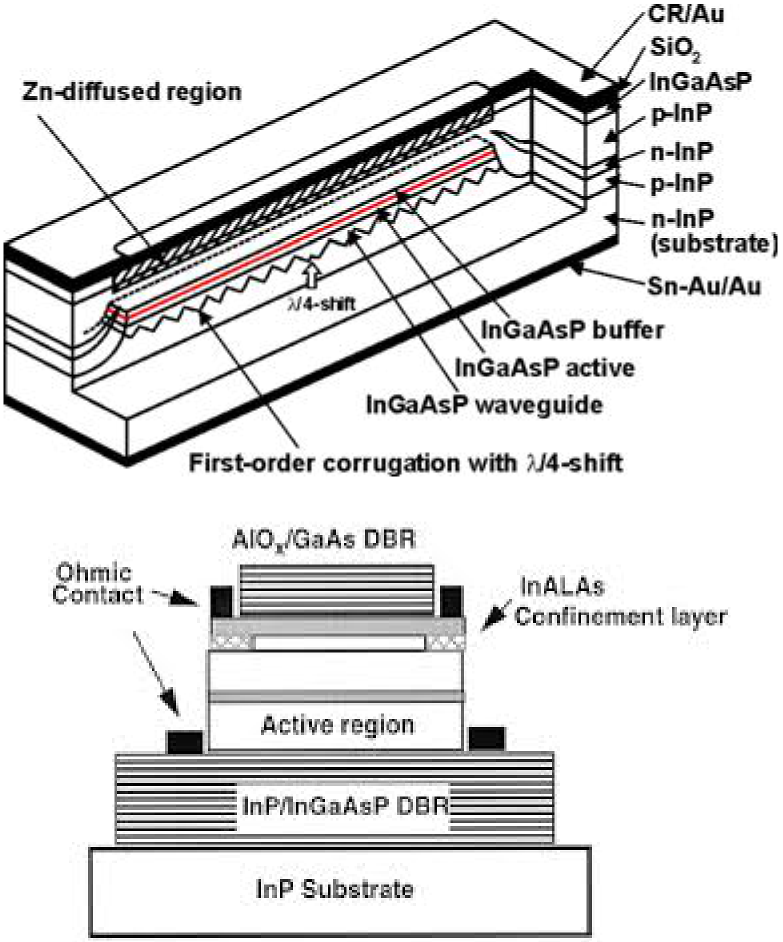


Figure 18. Laser Structure

(a) Turn them 90 degrees to create a very short Vertical Cavity Emitting Laser.

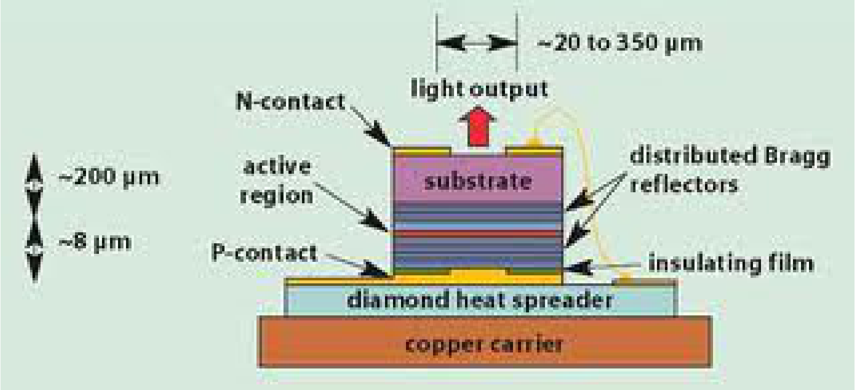


Figure 19. Laser Structure

18.3. PhotoDetectors

To detect light, simply run a semiconductor laser backwards!

When a p-n junction is formed in a semiconductor material, a region depleted of mobile charge carriers is formed with a high internal electric field across it known as the depletion region. If an electron-hole pair is generated by photon absorption within this region, the internal field will cause the electron and hole to separate as shown in the following figure (figure 20).

$$J_{ph} = -e\eta\phi \tag{18.5}$$

where

ϕ**:** Photons per second
η**:** Quantum efficiency

$$\eta = \frac{photocarriers\ generated}{photons\ absorbed} \tag{18.6}$$

We may detect this charge separation in two ways, shown in figure 21

- If the device is left on open circuit, an externally measurable potential will appear between the p and n regions. This is known as the ***photovoltaic*** mode of operation.
- On the other hand, we may short circuit the device externally (usually operated under reverse bias) in which case an external current flows between the p and n regions.

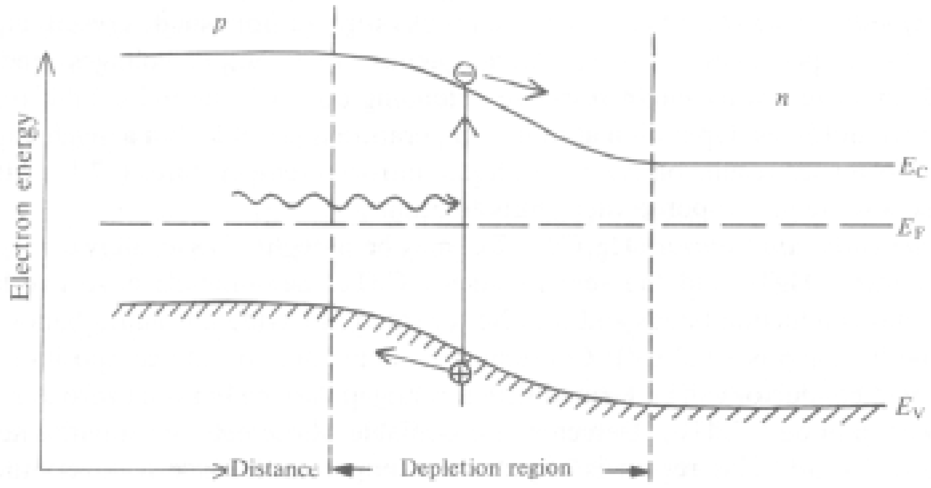


Figure 20. Energy Band Diagram, $J_{ph} = -e\eta\phi$

This is known as the ***photoconductive*** mode of operation.

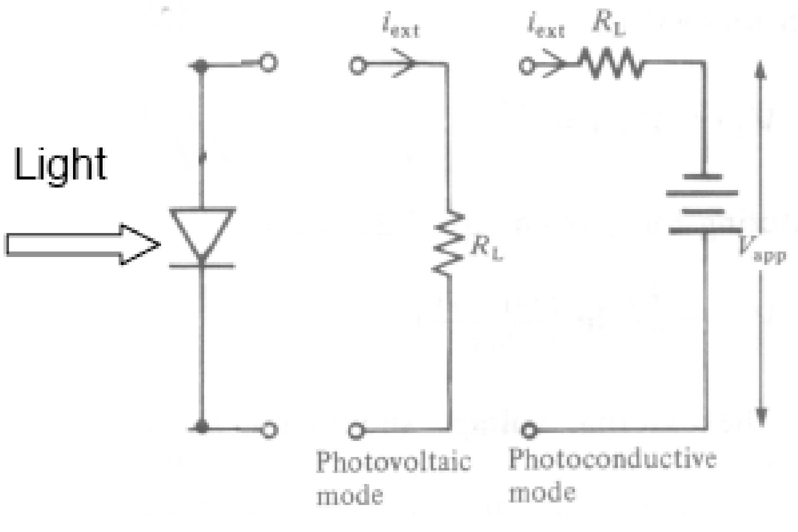


Figure 21. PhotoDetective modes

The current-voltage characteristics of a p-n junction under various levels of illumination is shown in the figure 22. The dark characteristic (absence of light) is that of an ordinary p-n junction diode. Under increasing levels of illumination the curve is progressively shifted downwards. **The main drawback is the presence of a dark current which limits the ultimate sensitivity of the device.**

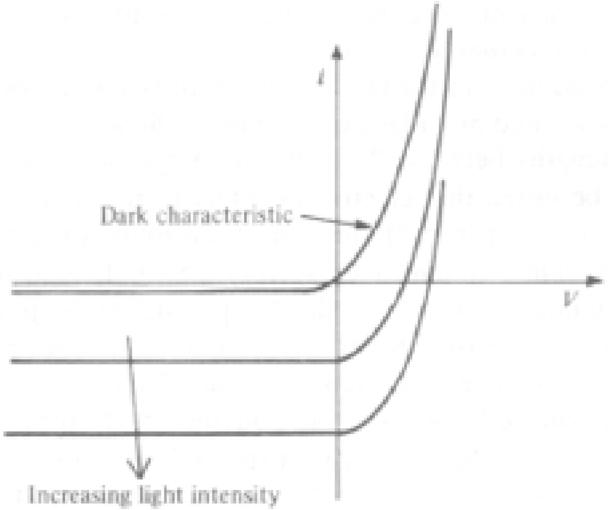


Figure 22. I-V curve

18.3.1. Structure

A simple pn photodiode is shown in figure 23. For high speed operation

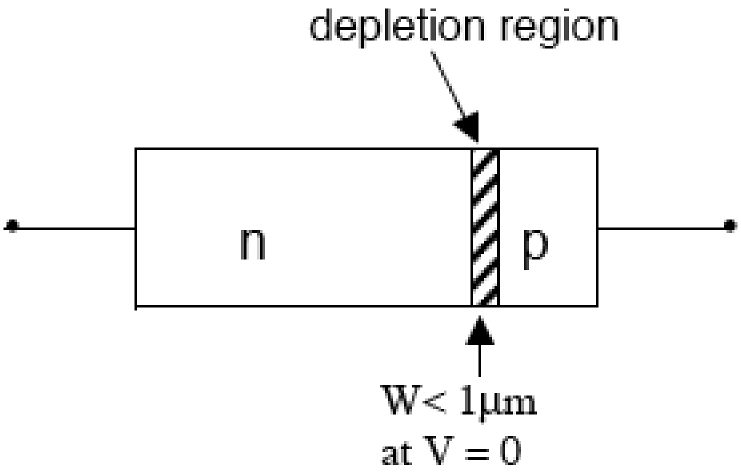


Figure 23. A simple PN diode structure

the depletion region must be kept thin to reduce the transit time of photocarriers. On the other hand, to increase the quantum efficiency, the depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed. Thus there is a trade-off between the speed of response and quantum efficiency. The depletion width is given by equation 18.7.

$$W = \sqrt{\frac{2\varepsilon_s(V_{bi} - V)}{qN_A}} \tag{18.7}$$

The depletion width is therefore a strong determinant of efficiency and speed of the device.

By introducing an intrinsic layer of material in between the junction a p-i-n diode is created. The depletion region thickness (the intrinsic layer) can be tailored to optimize the quantum efficiency and frequency response. We have a nominally intrinsic "i" layer, but in practice very lightly doped fully depleted region is formed. Photogenerated carriers are swept out of depletion region by high ε field and ideally, carriers move at $\sim V_{sat}$.

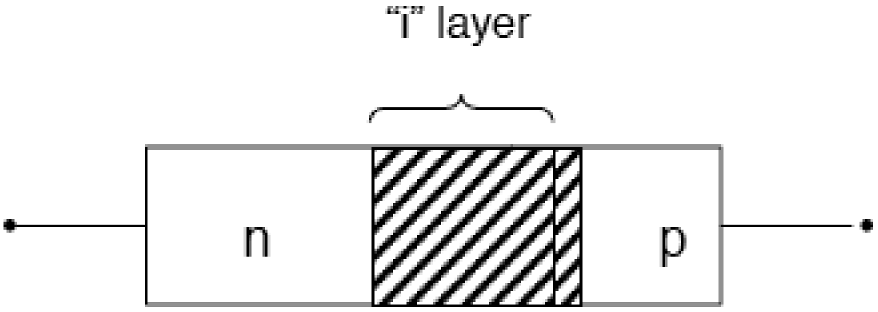


Figure 24. A PIN structure

18.3.2. Avalanche detectors

Useful internal amplification is achieved in the avalanche photodiode. In this device, a basic p-n structure is operated under very high (close to breakdown $\sim 100V$) reverse bias. In the very intense Electric field carriers can gain enough energy to enable other carriers to be excited across the energy gap by impact excitation. This results in an avalanche of carrier multiplication. **Thus, one photon produces many electrons/holes and lots of current (high sensitivity).** Figure 25 illustrates the principle of operation of an avalanche photodiode. An electron having reached the point A has sufficient energy above the conduction band bottom to enable it to excite an electron from the valence band into the conduction band (CD). In doing so, it falls from A to B.

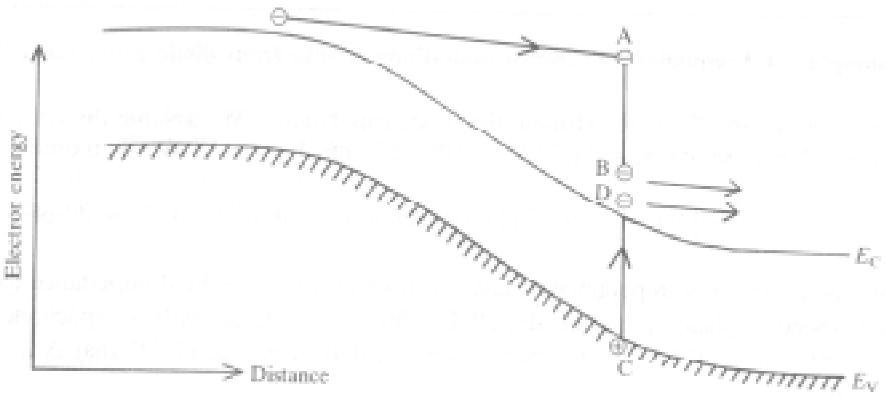


Figure 25. Avalanche

18.3.3. Photodetector materials

- Silicon:
  - band gap energy $= 1.1\,eV$, sensitive for $\lambda < 1100\,nm$
  - indirect gap
  - cheap, mature technology
- Germanium:
  - band gap energy $= 0.7\,eV$, works in telecommunications range
  - direct gap for $\lambda < 1550\,nm$
  - difficult material
- GaAs:

  - band gap energy = $1.5\,eV$, sensitive for $\lambda < 860\,nm$
  - direct gap
- InGaAsP:
  - band gap energy = $0.7\,eV$, works in telecommunications range
  - direct gap