Chapter 4

Optical Sources

Introduction

Convert electrical energy in the form of a current into optical energy which allows the light output to be effectively coupled into the optical fiber.

Two types

(a) Light emitting diodes (LED) - incoherent source.
(b) Laser - coherent source.

Requirements :

1. Size and configuration - compatible with launching light into an optical fiber. Ideally the light output should be highly directional.
2. Must accurately track the electrical input signal to minimize distortion and noise. Ideally the source should be linear.
3. Should emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient.
4. Preferably capable of simple signal modulation over a wide bandwidth extending from audio frequencies to beyond the GHz range.

5. Must be capable of maintaining a stable optical output which is largely unaffected by changes in ambient conditions (e.g. temperature).
6. It is essential that the source is comparatively cheap and highly reliable in order to compete with conventional transmission techniques.
7. Should have a very narrow spectral width (line width) in order to minimize dispersion in the fiber.

Basic Concepts

In this context the requirements for the laser source are far more stringent than those for the LED. Unlike the LED, the laser is a device, which amplifies light. Hence the derivation of the term LASER as an acronym for **L**ight **A**mplification by **S**timulated **E**mission **R**adiation.

By contrast the LED provides optical emission without an inherent gain mechanism which results in incoherent light output.

Absorption and Emission of Radiation

- The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the higher energy state E_2 and the lower energy state E_1 by the expression:

  $E = E_2 - E_1 = hf$, where $h = 6.626 \times 10^{-34}$ J s is Planck's constant.

- Figure 5.1 (a) illustrates a two energy state or level atomic system where an atom is initially in the lower energy state E1.

- When a photon with energy ($E_2 – E_1$) is incident on the atom it may be excited into the higher energy state E_2 through absorption of the photon.
- Alternatively when the atom is initially in the higher energy state E_2 it can make a transition to the lower energy state E_1 providing the emission of a photon at a frequency corresponding to equation stated above.

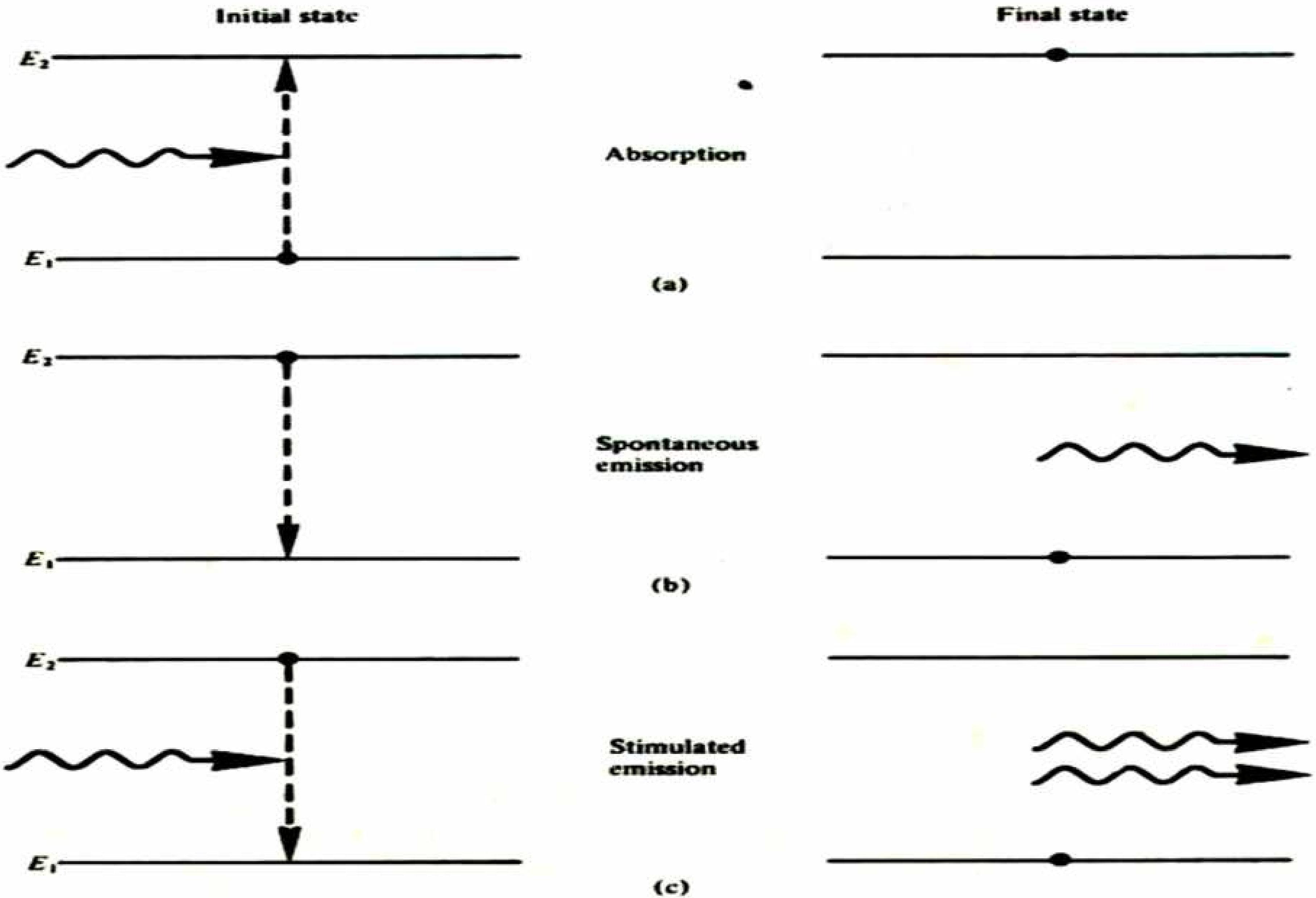
- This emission process can occur in two ways:

  (a) Spontaneous emission in which the atom returns to the lower energy state in an entirely random manner.

  (b) Stimulated emission when a photon having an energy equal to the energy difference between the two states ($E_2 - E_1$) interacts with the atom in the upper energy state causing it to return to the lower state with the creation of a second photon.

These two emission are illustrated in Fig. 5.1 (b) and (c)

Figure 5.1



Energy state diagram showing: (a) absorption; (b) spontaneous emission; (c) stimulated emission. The black dot indicates the state of the atom before and after a transition takes place.

LED:

The random nature of the spontaneous emission process where light is emitted by electronic transitions from a large number of atoms gives incoherent radiation.

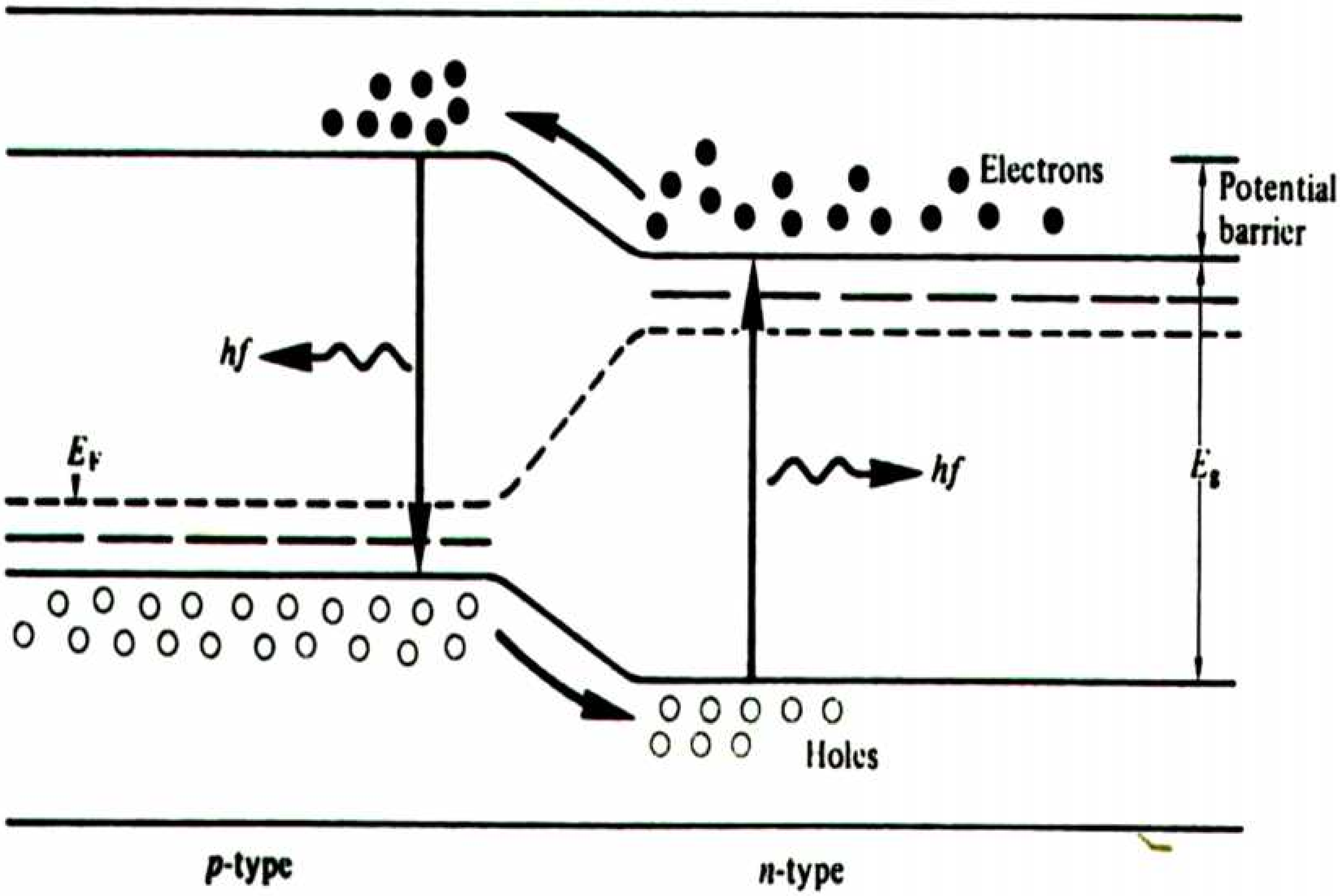
LASER: It is the stimulated emission process which gives the laser its special properties as an optical source.

1. The photon produced by stimulated emission is generally of an identical energy to the one which caused it and hence the light associated with them is of the same frequency - Monochromatic
2. The light associated with the stimulating and stimulated photon is in phase and has the same polarization – Coherent.

- Furthermore this means that when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in a constructive manner, providing amplification.

- Therefore, in contrast to spontaneous emission, coherent radiation is obtained.

Figure 5.2



The *p–n* junction with forward bias giving spontaneous emission of photons.

- The energy released by this electron-hole recombination is approximately equal to the bandgap energy E_g.
- The energy is released with the creation of a photon with a frequency following equation where the energy is approximately equal to the bandgap energy E_g and therefore:

E_g ù hf

Stimulated Emission and Lasing

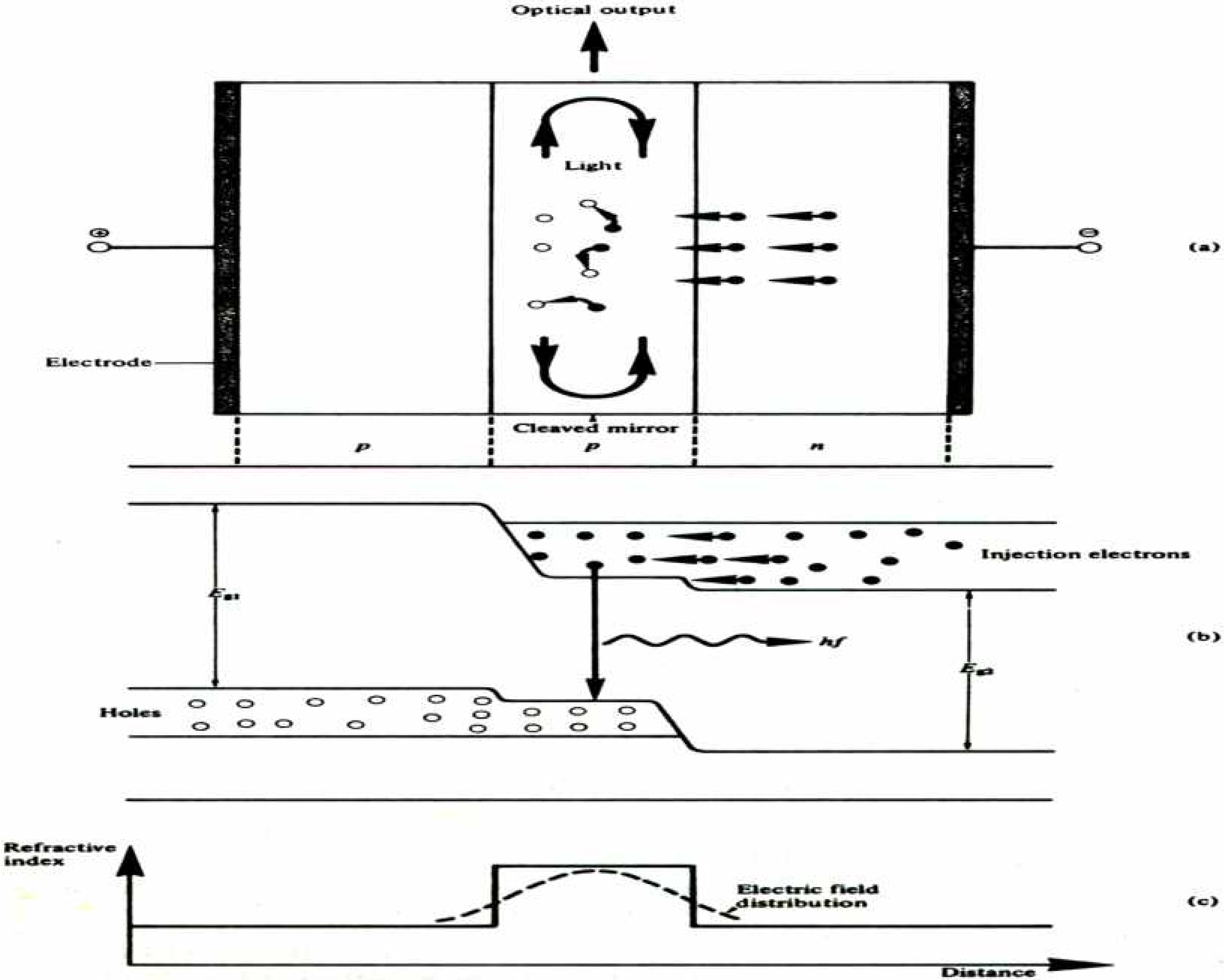
- The general concept of stimulated emission is via population inversion and optical feedback.
- Carrier population inversion is achieved in an intrinsic semiconductor by the injection of electrons into the conduction band of the material.

Heterojunction

- The previous sections have considered the photoemissive properties of a single p-n junction fabricated from a single crystal semiconductor material known as a homojunction.
- However the radiative properties of a junction diode may be improved by the use of heterojunctions.
- A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap energies.
- This technique is widely used for the fabrication of injection lasers and high radiance LED.

Heterojunction provides:

- Radiation confinement
- Carrier confinement



The double heterojunction injection laser: (a) the layer structure, shown with an applied forward bias; (b) energy band diagram indicating a p–p heterojunction on the left and a p–n heterojunction on the right; (c) the corresponding refractive index diagram and electric field distribution.

Semiconductor Materials

Must fulfill:

1. **Efficient electroluminescence. The** devices fabricated must have a high probability of radiative transitions and therefore high internal quantum efficiency.

2. **Useful emission wavelength**. The materials must emit light at a suitable wavelength to be utilized with current optical fibers and detectors (0.8-1.7µm).

Some common material used in the fabrication of sources for optical fiber communications.

Material active layer/confining layers	Wavelength range (µm)	Substrate
$GaAs/Al_xGa_{1-x}As$	0.8-0.9	GaAl
$GaAs/In_xGa_{1-x}P$	0.9	GaAs
$Al_yGa_{1-y}As$ /$Al_xGa_{1-x}As$	0.65-0.9	GaAs
$In_yGa_{1-y}As$ /$In_xGa_{1-x}P$	0.85-1.1	GaAl
$GaAs_{1-x}Sb_x$ /$Ga_{1-y}Al_yAs_{1-x}Sb_x$	0.9-1.1	GaAs
$Ga_{1-y}Al_yAs_{1-x}Sb_x/GaSb$	1.0-1.7	GaSb
$In_{1-x}Ga_xAs_yP_{1-y}/InP$	0.92-1.7	InP

Material	$\lambda(\mu m)$	$E_g(eV)$
GaInP	0.64-0.68	1.82-1.94
GaAs	0.9	1.4
AlGaAs	0.8-0.9	1.4-1.55
InGaAs	1.0-1.3	0.95-1.24
InGaAsP	0.9-1.7	0.73-1.35

Emission wavelength, $\boldsymbol{\lambda = (1.24/E_g)}$ where E_g = gap energy in eV. Different material and alloys have different bandgap energies.

- The GaAs/AIGaAs DH system is currently by far the best developed and is used for fabricating both lasers and LEDs for the shorter wavelength region.

- The bandgap in this material may be ’tailored’ to span the entire 0.8 µm - 0.9 µm wavelength band by changing the AlGa composition.

- In the longer wavelength region (l.l µm - l.6µm) a number of III-V alloys have been used which are compatible with GaAs, InP and GaSb substrates.

Laser Sources

LASER requires:

- Population inversion.
- Optical feedback.

Types: Gas laser, Semiconductor laser and Solid-state laser

Population Inversion

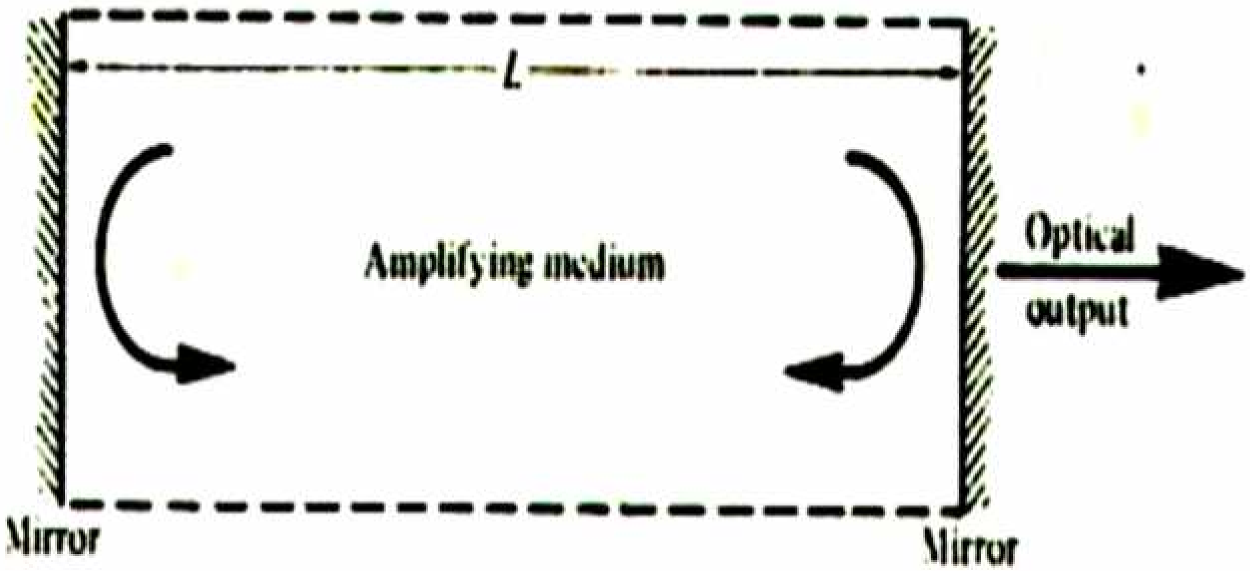
- Under the normal conditions the lower energy level E_1 of the two level atomic system contains more atoms than the upper energy level E_2.
- However, to achieve optical amplification it is necessary to create a non-equilibrium distribution of atoms such that the population of atoms in the upper energy level is greater than that of the lower energy level (i.e. $N_2 > N_1$).
- This condition is known as **population inversion** and achieved using an external energy source and also known as 'pumping'.

B. Optical Feedback And Laser Oscillation

- Light amplification in laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more.
- Continuation of this process effectively creates multiplication, and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained

- To achieve this laser action it is necessary to **contain photons within the laser medium** and maintain the conditions for coherence.
- This is accomplished by placing or forming mirrors at either end of the amplifying medium.
- Furthermore, if one mirror is made partially transmitting, useful radiation may escape from the cavity.

Figure 5.3



The basic laser structure incorporating plane mirrors.

The Semiconductor Injection Laser

- Stimulated emission by the recombination of the injected carriers is encouraged in the semiconductor injection laser (ILD) by the provision of an optical cavity in the crystal structure in order to provide the feedback of photons.
- This gives the injection laser several major advantages over other semiconductor sources that may be used for optical communications.

These are:

1. High radiance due to the amplifying effect of stimulated emission. Injection lasers will generally supply mW of optical output power.

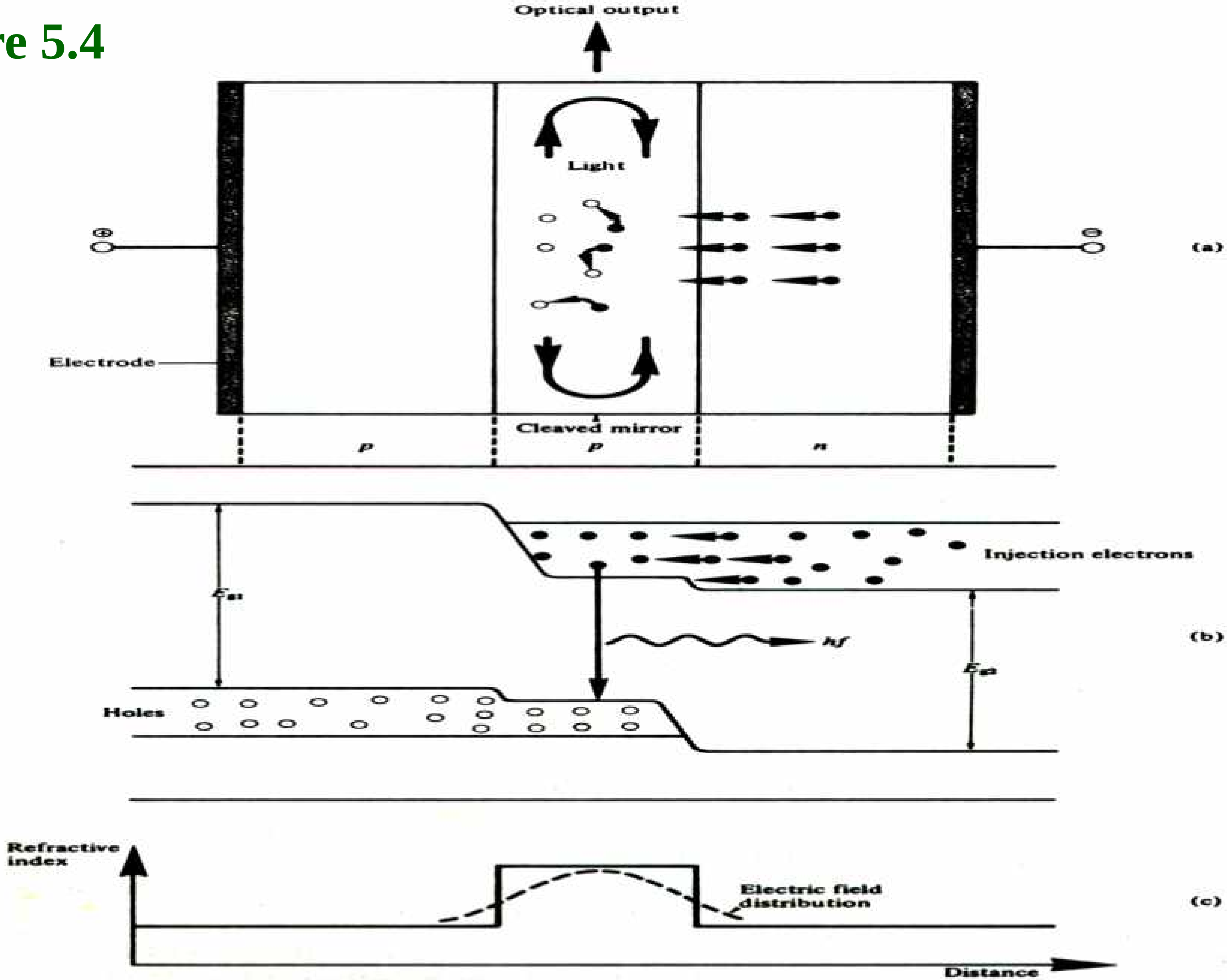
2. Narrow linewidth of the order of 1 nm or less which is useful in minimizing the effects of material dispersion.

3. Modulation capabilities which at present extend up into the GHz range.

4. Relative temporal coherence which is considered essential to allow heterodyne (coherent) detection in high capacity systems, but at present is primarily of use in single mode systems.

5. Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than the dispersed unfocused emission. This permits efficient coupling of the optical output power into the fiber even for fibers with low numerical aperture.

Figure 5.4



The double heterojunction injection laser: (a) the layer structure, shown with an applied forward bias; (b) energy band diagram indicating a p–p heterojunction on the left and a p–n heterojunction on the right; (c) the corresponding refractive index diagram and electric field distribution.

Injection Laser Characteristics

1. Threshold Current Temperature Dependence
2. Dynamic Reponse
3. Efficiency

- There are a number of ways in which the operational efficiency of the semiconductor laser may be defined.

- One parameter is the total efficiency (external quantum efficiency) η_T which is efficiency defined as:

$$\eta_T = \frac{\text{total number of output photons}}{\text{total number of injected electrons}}$$

- The external power efficency of the device η_{ep} in converting electrical input to optical output is given by:

$$\eta_{ep} = \frac{P_e}{P} \times 100\ \%$$

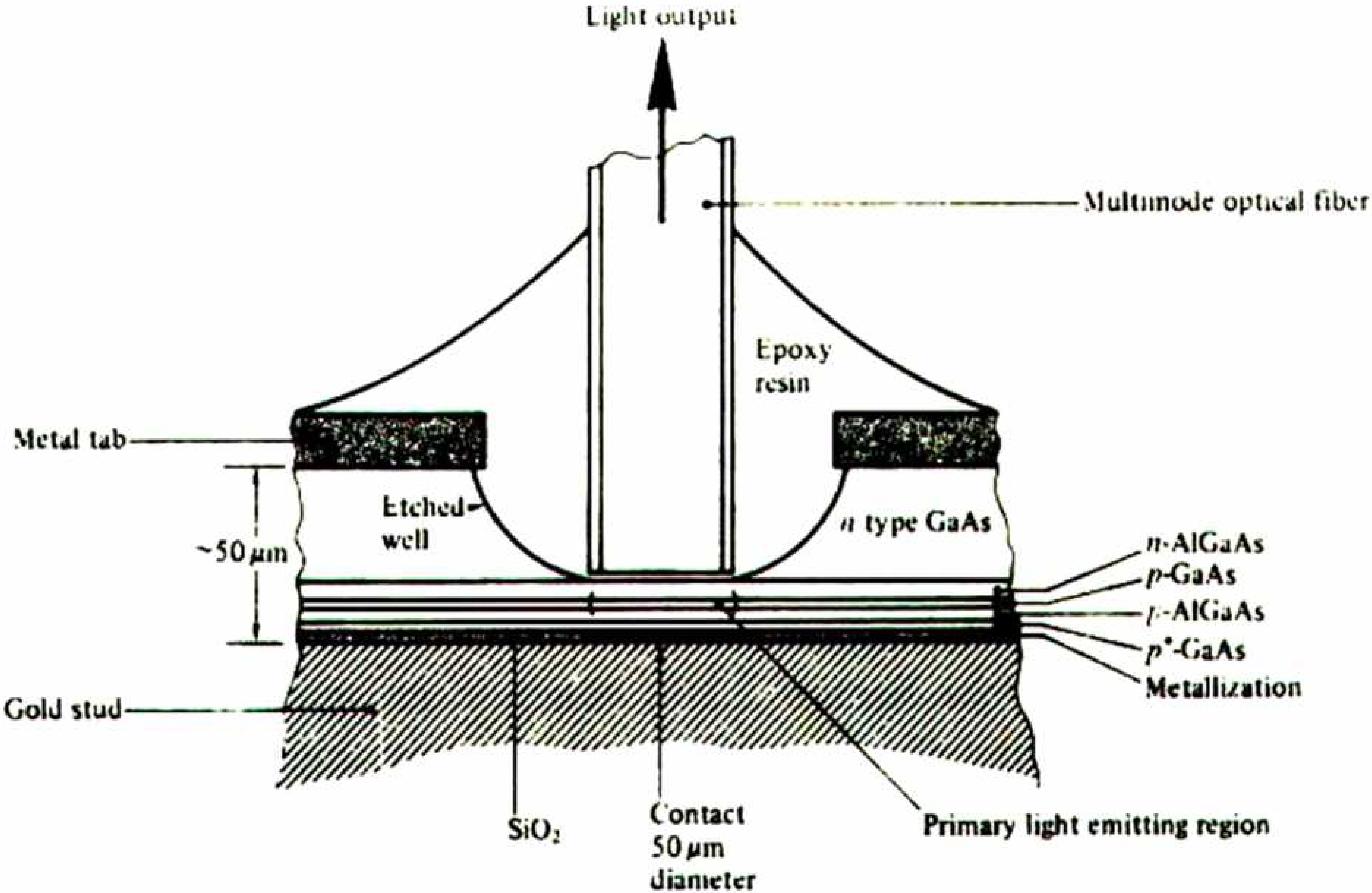
$$= \eta_T \left(\frac{E_g}{V} \right) \times 100\,\%$$

where P=IV is the d.c. electrical input power and P_e = power emitted

4. Reliability

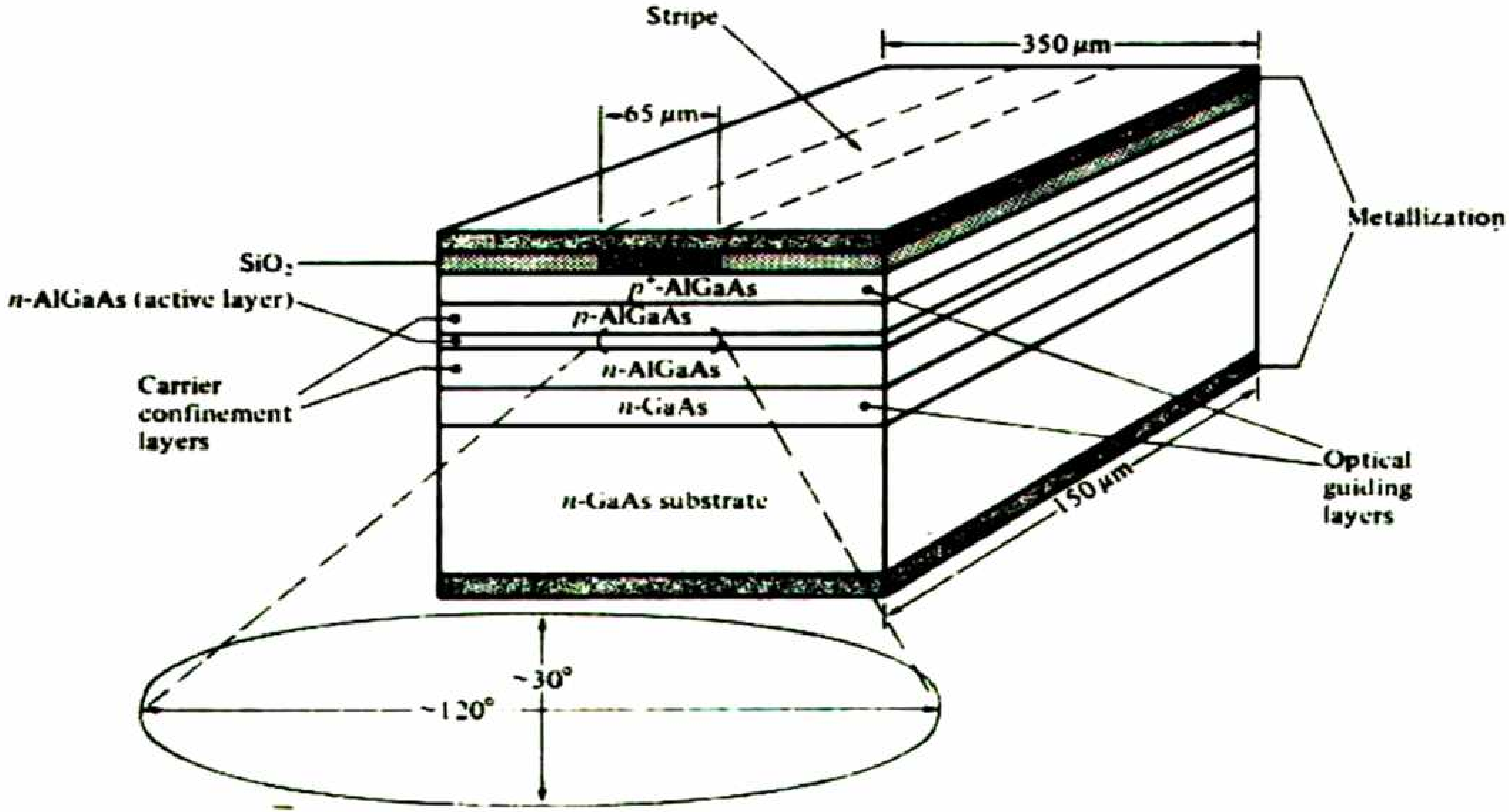
- Device reliability has been a major problem with injection lasers and although it has been extensively studied, not all aspects of the failure mechanisms are fully understood. Nevertheless, much progress has been made since the early days when device lifetimes were very short (a few hours).

Surface Emitter (Burrus Type) LED

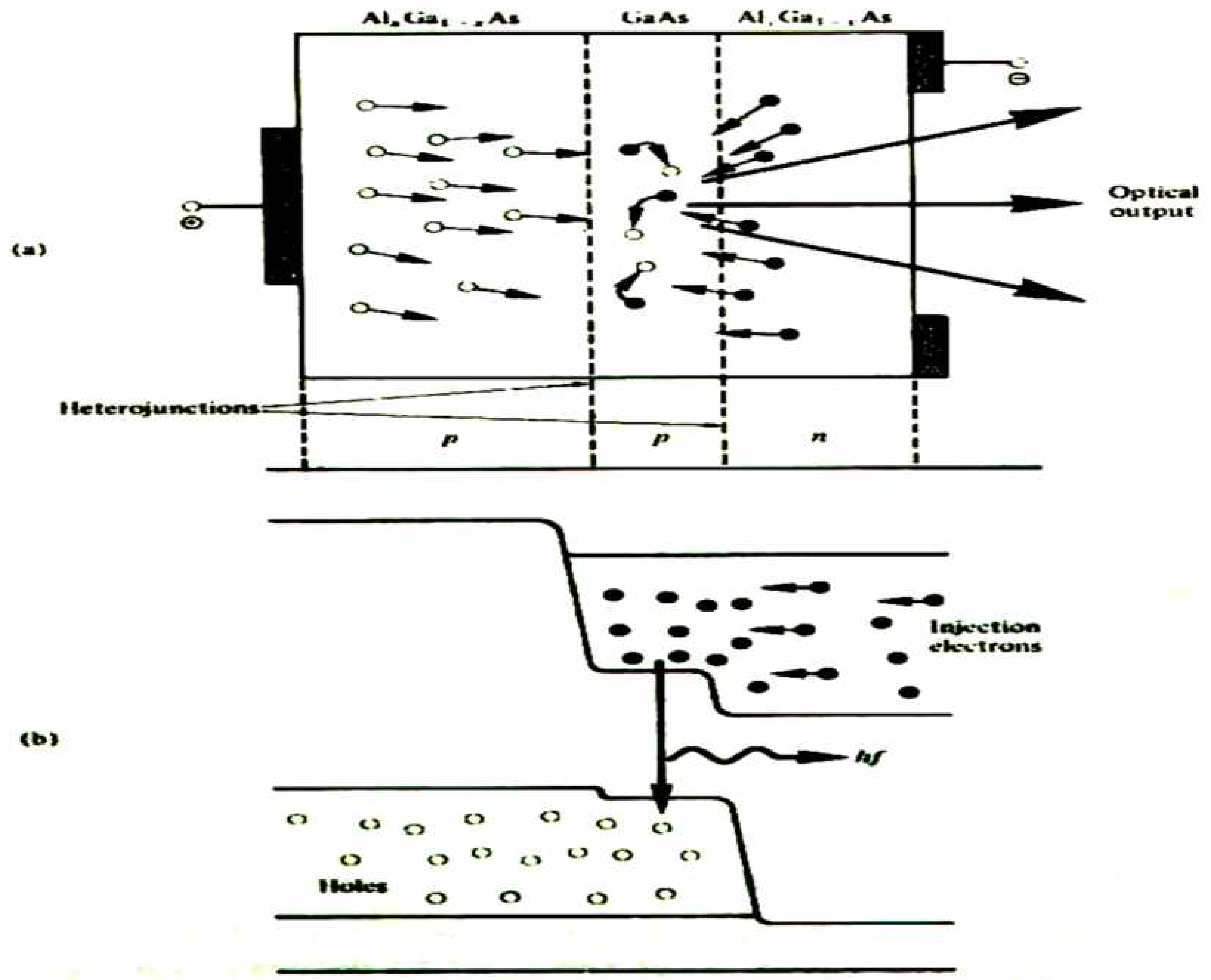


The structure of an AlGaAs DH surface-emitting LED (Burrus type) [Ref. 7].

Edge Emitter LED



Schematic illustration of the structure of a stripe geometry DH AlGaAs edge-emitting LED.



The double heterojunction LED: (a) the layer structure, shown with an applied forward bias; (b) the corresponding energy band diagram.

LED Efficiency

- The absence of optical amplification through stimulated emission in the LED tends to limit the internal quantum efficiency (ratio of photons generated to injected electrons) of the device.
- Reliance on spontaneous emission allows nonradiative recombination to take place within the structure due to crystalline imperfections and impurities giving at best an internal quantum efficiency of 50% for simple homojunction devices.

- However, as with injection lasers double heterojunction (DH) structures have been implemented which recombination lifetime measurements suggest give internal quantum efficiencies of 60-80%.

- The external power efficency of the device η_{ep} in converting electrical input to optical output is given by:

$$\eta_{ep} = \frac{P_e}{P} \times 100 \ \%$$

$$= \eta_T \left(\frac{E_g}{V} \right) \times 100 \ \%$$

where P=IV is the d.c. electrical input power and P_e = power emitted

- The optical power emitted P_e into a medium of low refractive index n from the face of a planar LED fabricated from a material of refractive index n, if given approximately by:

$$P_e = \frac{P_{\text{int}} F n^2}{4 n_x^2}$$

where P_{int} is the power generated internally and F is the transmission factor of the semiconductor-external interface.

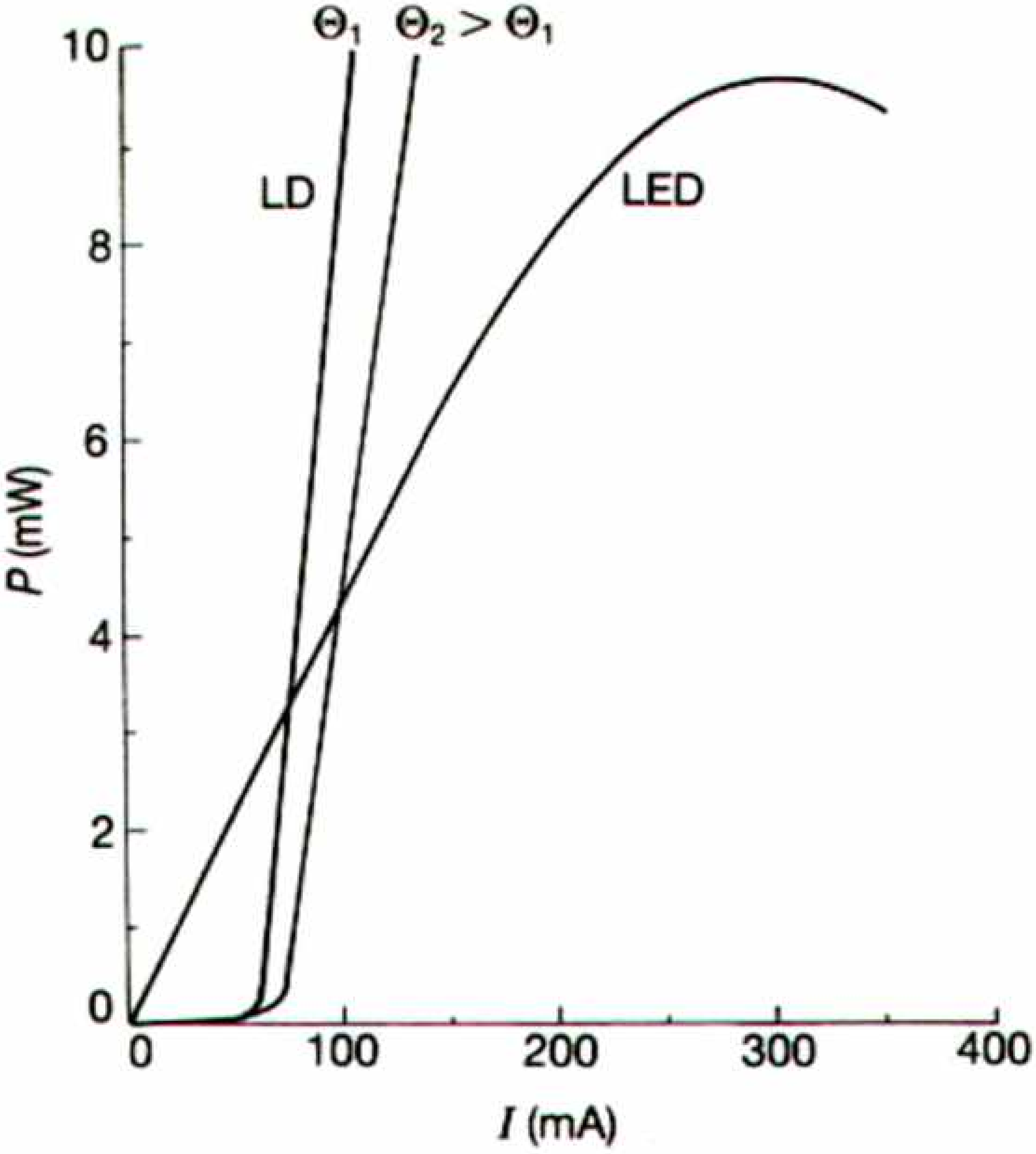
- Hence it is possible to estimate the percentage of optical power emitted.

Semiconductor laser versus LED

When deciding whether to choose an LED or an LD as the light source in a particular optical communication system, the main features to be considered are the following:

- The optical power versus current characteristics of the two devices differ considerably.
- Near the origin the LED characteristic is linear, although it becomes non-linear for larger power values.
- However, the laser characteristic is linear above the threshold.

- The power supplied by both devices is similar (about 10-20 mW).
- However, the maximum coupling efficiency of a fiber is much smaller for an LED than for a LD; for an LED it is 5-10 percent, but for an LD it can be up to 90 percent.
- This difference in coupling efficiency has to do with the difference in radiation geometry of the two devices
- The power-to-current characteristic of an LD depends greatly on temperature, but this dependence is not so great for an LED.



Power versus current characteristic of an LD and an LED.

- As an LED emits spontaneous radiation, the speed of modulation is limited by the spontaneous recombination time of the carriers.
- LEDs have a large capacitance and modulation bandwidths are not very large (a few hundred megahertz).

- LDs have narrower spectra than LEDs, and the single-mode lasers, in particular have a very narrow spectrum. This explains why the pulse broadening at transmission through an optical fiber is very small. Therefore, with an LD as a light source, wideband transmission systems can be designed. The spectrum of an LD remains more stable with temperature than that of an LED.

- Changes of power output for an LD with temperature can be prevented by stabilizing the heat sink temperature. This generally requires more complicated electronic circuits than for an LED. The expected lifetime of both an LD and an LED is around 10’ hours, which is sufficient for practical purposes. LEDs can withstand power overloading for short duration better than LDs.
- At current prices, LEDs are less expensive than LDs.

Comparison between laser and LED

Property	LED	Laser Diode	Laser Diode
Spectral Width (nm)	20-100	1-5	<0.2
Risetime (ns)	2-250	0.1-1	0.05-1
Modulation BW (MHz)	<300	2000	6000
Coupling efficiency	Very low	Moderate	High
Compatible fiber	Multimode SI Multimode GRIN	Multimode GRIN Singlemode	Singlemode
Temperature sensitivity	Low	High	High
Circuit complexity	Simple	complex	Complex
Lifetime (hours)	10^5	10^4-10^5	$10^{4-}10^5$
Cost	Low	High	Highest
Primary use	Moderate paths Moderate data rates	Long paths High data rates	Very long paths Very high rates

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