COURSE: *OPTICAL COMMUNICATION* (EC317)

UNIT-III OPTICAL SOURCES

LASER

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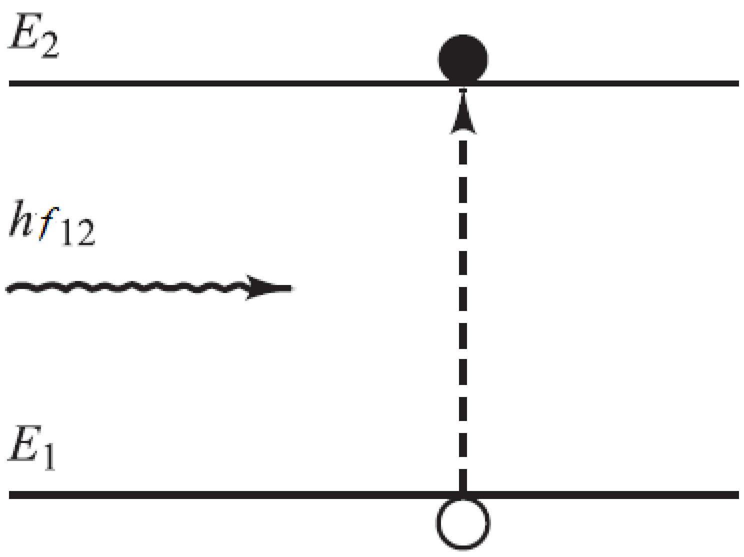
BASIC CONCEPTS (LASER)

- Unlike the LED, the laser is a device which amplifies light –**Light Amplification by Stimulated Emission of Radiation**
- The lasing medium can be a gas, a liquid, an insulating crystal (solid state), or a semiconductor.
- For optical fiber systems, the laser sources are used exclusively semiconductor laser diodes.
- Laser action is the result of three key processes:
  - photon absorption
  - spontaneous emission
  - stimulated emission

BASIC CONCEPTS (LASER): ABSORPTION

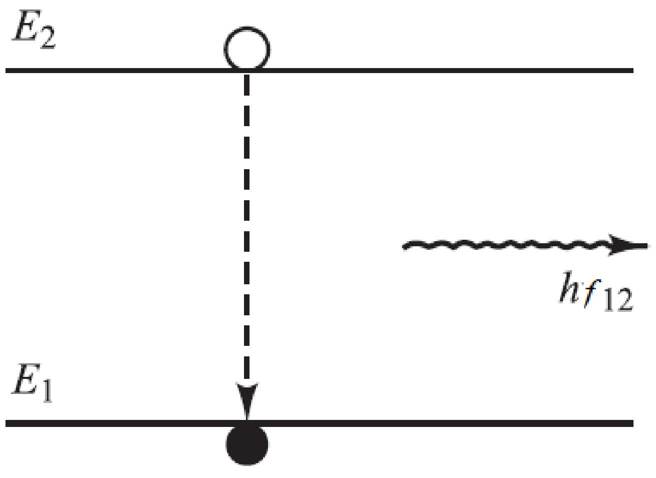
- According to Planck's law, a transition from one state of energy to another involves the absorption and emission of photon (light) of energy $E = E_2 – E_1 = hf$
- When a photon of energy impinges on the system, an electron in the ground state E_1 can absorb the photon energy and be excited to the exited state $E_{2.}$ This phenomenon is called **absorption**.



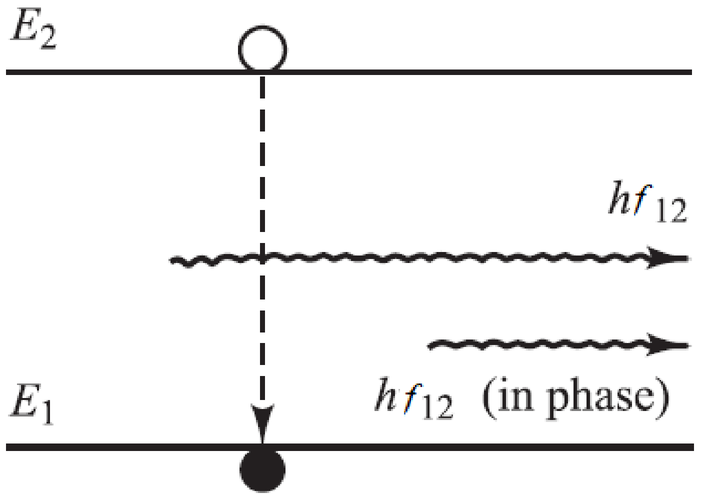
Absorption

BASIC CONCEPTS (LASER): EMISSION

- **Spontaneous emission:**
  - If the atom is in the ground state, with energy E_1, the photon may be absorbed so that it is excited to the upper level of energy E_2. Since this is an unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy. This is called spontaneous emission
  - entirely random manner and it gives incoherent radiation
- **Stimulated emission:**
  - If the atom is already in the excited state, then the incident photon may stimulate a downward transition with the emission of radiation.
  - Both are in phase and same polarization, therefore coherent radiation is obtained
  - When an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave, providing amplification.



Spontaneous emission



Stimulated emission

BASIC CONCEPTS (LASER):

- In thermal equilibrium, spontaneous emission is the dominant mechanism, that the radiation emitted from optical source in the visible spectrum occurs in a random manner, providing these sources are incoherent.
- In order to produce a coherent optical source and amplification of light beam, the rate of stimulated emission must be increased far above the lower level. This condition is known as **Population Inversion.**
- Population inversion is achieved by various **pumping** techniques (i.e., injecting electrons into the material to fill the lower energy states of the conduction band).

THE EINSTEIN RELATIONS: OPTICAL AMPLIFICATION IN THE TWO-LEVEL ATOMIC SYSTEM

- Let consider N_1 and N_2 are the density of electrons in energy levels E_1 and E_2
- The rate of **absorptive transitions** of electrons from the ground state (level 1) to the excited state (level 2) is directly proportional to the density of electrons in the ground state and the spectral density $\rho(f)$ of the radiation energy at the transition frequency f

$$R_{12} = B_{12} N_1 \rho(f)$$

- The rate of **spontaneous emission** as a result of electron transitions from the excited state to the ground state is directly proportional to the number of electrons in the excited state.

$$R_{21}(spont.) = A_{21} N_2$$

- The rate of **stimulated downward transition** of an electron from level 2 to level 1 may be obtained in a similar manner to the rate of stimulated upward transition.

$$R_{21}(Stimu.) = B_{21} N_2 \rho(f)$$

- For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore $R_{12} = R_{21}$,

$$B_{12} N_1 \rho(f) = A_{21} N_2 + B_{21} N_2 \rho(f)$$

where the proportionality constants B_{12}, A_{21}, and B_{21} are known as the Einstein coefficients

The spectral density $\rho(f)$ of the radiation energy

$$\rho(f) = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}N_1}{B_{21}N_2} - 1}$$

We know that

$$\frac{N_1}{N_2} = e^{\frac{hf}{kT}}$$

$$\rho(f) = \frac{8\pi hf^3}{c^3}\frac{1}{e^{\frac{hf}{kT}} - 1}$$

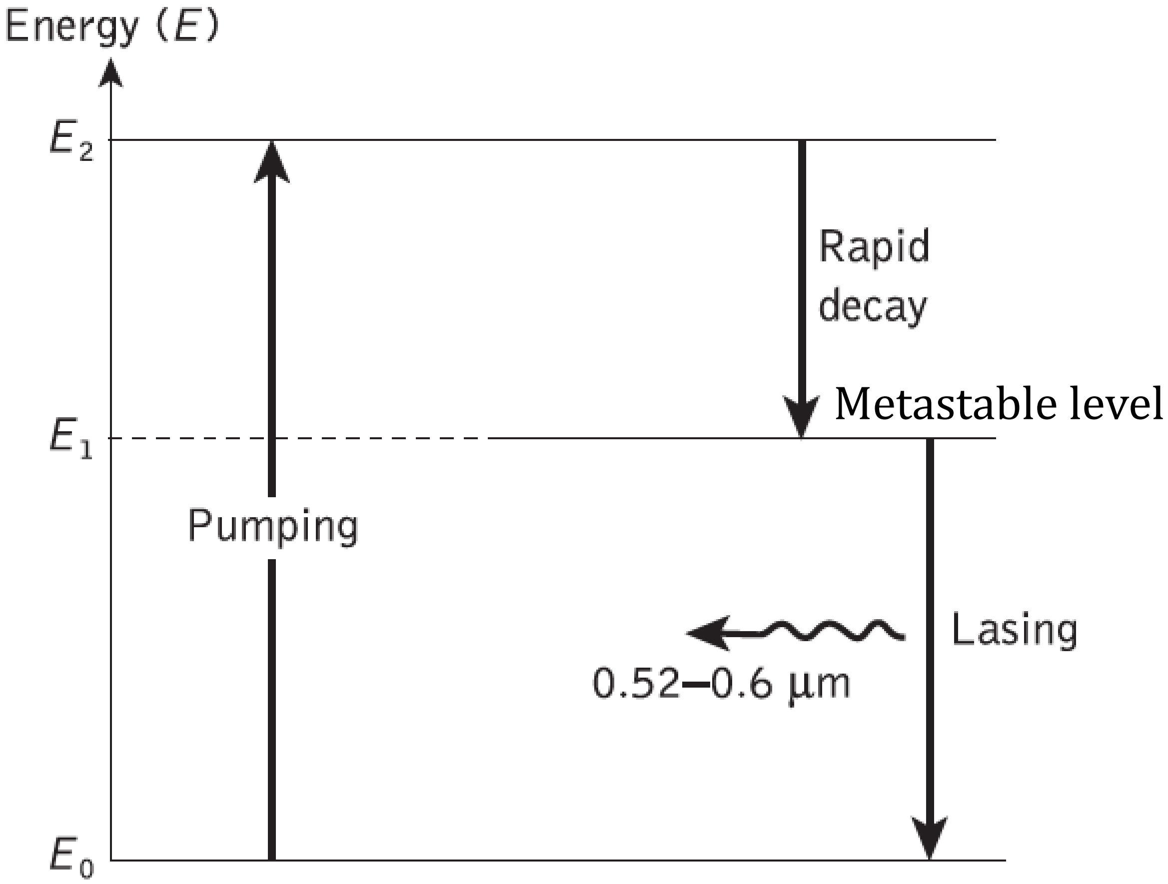
Where $\frac{A_{21}}{B_{21}} = \frac{8\pi hf^3}{c^3}$ and $B_{12} = B_{21}$;

- The ratio of the stimulated emission rate to the spontaneous emission rate is given by

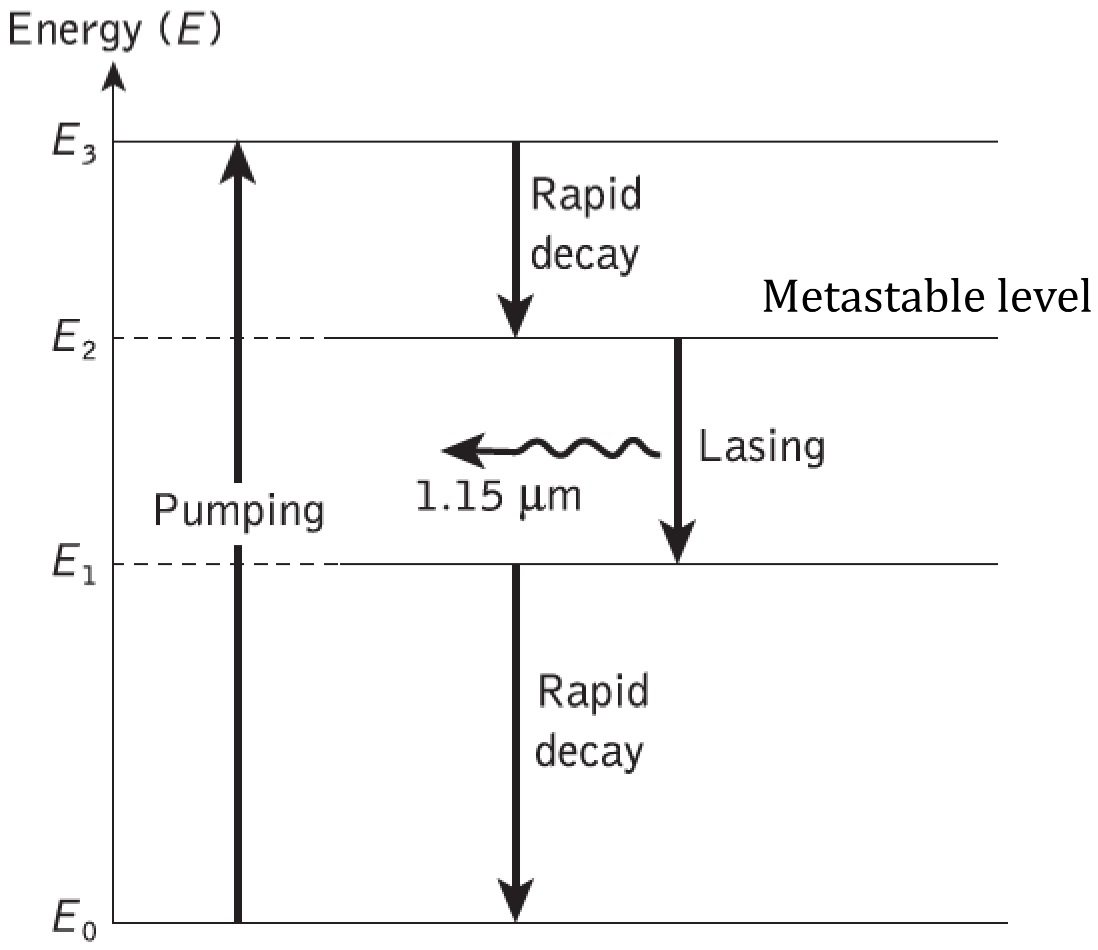
$$\frac{B_{21}\rho(f)}{A_{21}} = \frac{1}{e^{\frac{hf}{kT}} - 1}$$

POPULATION INVERSION

- In order to produce stimulated emission, it is essential to create a non-equilibrium situation in which the population of atoms in the upper energy level is greater than that in the lower energy level, that is, $N_2 > N_1$. This non-equilibrium condition is called **population inversion**.
- In order to achieve population inversion it is necessary to excite atoms into the upper energy level E_2 and hence obtain a nonequilibrium distribution. This process is achieved using an external energy source and is referred to as '**pumping**'.
- In a two-level atomic system that is pumped externally, stimulated emission cannot become a dominant process because it has to compete with stimulated absorption
- either three-level or four-level atomic systems are used for achieving laser action (population inversion)



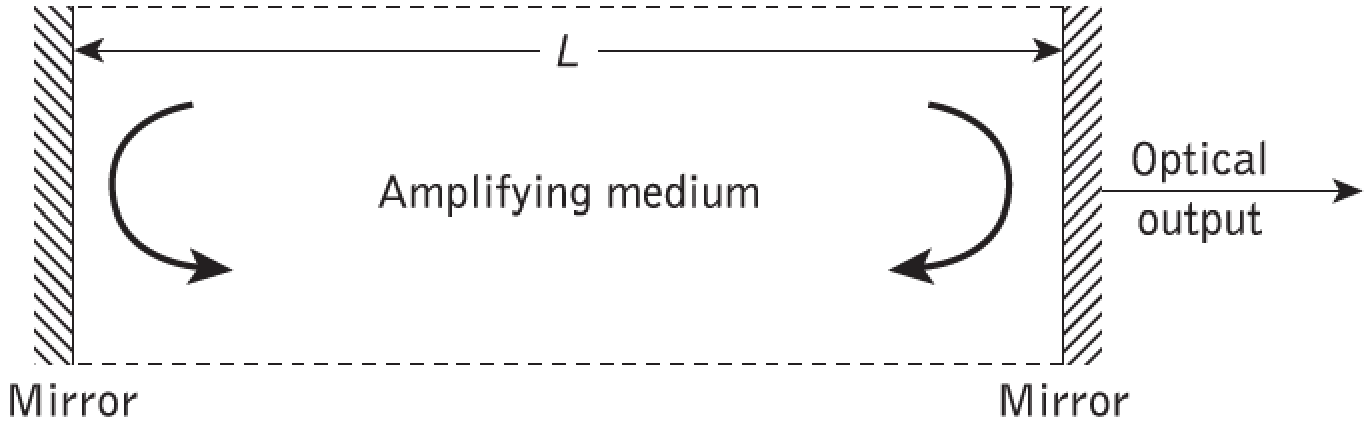
- The metastable level E_1 exhibits a much longer lifetime than E_2 which allows a large number of atoms to accumulate at E_1.
- Over a period the density of atoms in the metastable state N_1 increases above those in the ground state N_0 and a population inversion is obtained between these two levels.
- Stimulated emission and hence lasing can then occur, creating radiative electron transitions between levels E_1 and E_0.



Energy (E)
E3
E2
E1
E0
Rapid
decay
Metastable level
Lasing
1.15 μm
Pumping
Rapid
decay

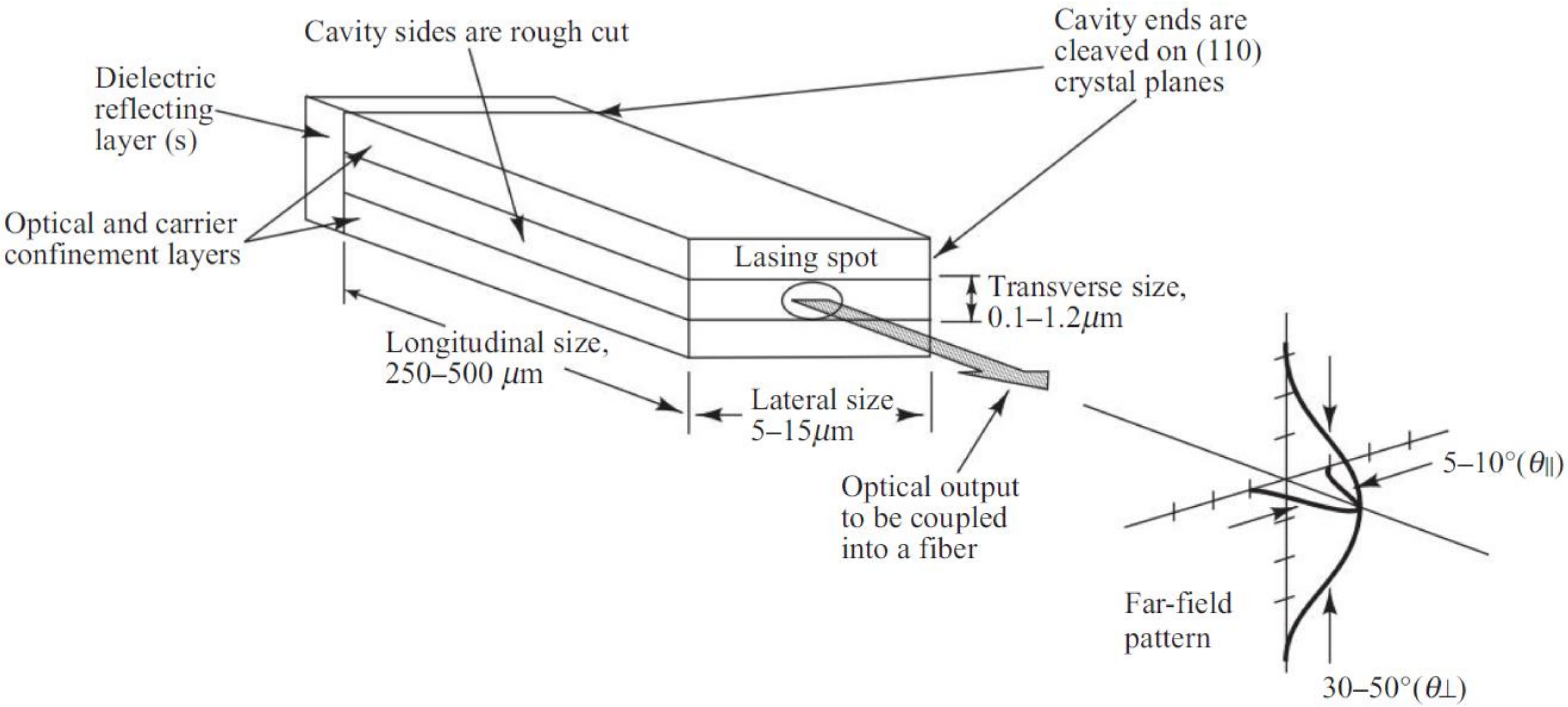
OPTICAL FEEDBACK AND LASER OSCILLATION

- Light amplification in the 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 and so on (avalanche 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 **place or form mirrors** (plane or curved) at either end of the amplifying medium.



OPTICAL FEEDBACK AND LASER OSCILLATION

- The positive feedback of the photons by reflection at the mirrors at either end of the cavity gives an oscillatory condition than an amplifier (optical cavity). This structure is called a **Fabry– Pérot resonator**.
- If one mirror is made partially transmitting, useful radiation may escape from the cavity.
- A stable output is obtained at saturation when the **optical gain is exactly matched by the losses** incurred in the amplifying medium.
- The major losses result from factors such as absorption and scattering in the amplifying medium, absorption, scattering and diffraction at the mirrors and non-useful transmission through the mirrors.
- Oscillations occur in the laser cavity over a small range of frequencies where the cavity gain is sufficient to overcome the above losses.



Fabry-Perot resonator cavity for a LASER diode

THRESHOLD CONDITION FOR LASING ACTION

- Lasing occurs when the gain of one or several guided modes is sufficient to exceed the optical loss during one roundtrip (z = 2L) through the cavity.
- During this roundtrip, only the fractions R_1 and R_2 of the optical radiation are reflected from the two laser ends 1 and 2, respectively
- On each round trip the beam passes through the medium twice. Hence the fractional loss incurred by the light beam is: $R_1 R_2 e^{-2\alpha L}$
- If the gain coefficient per unit length produced by stimulated emission is g cm^{-1}, the fractional round trip gain is given by: e^{2gL}
- The optical field intensity

$$I(2L) = I(0) R_1 R_2 e^{2(g-\alpha)L}$$

At the lasing threshold

$$R_1 R_2 e^{2(g_{th}-\alpha)L} = 1$$

$$g_{th} = \alpha + \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

RESONANT FREQUENCIES AND LASER MODES

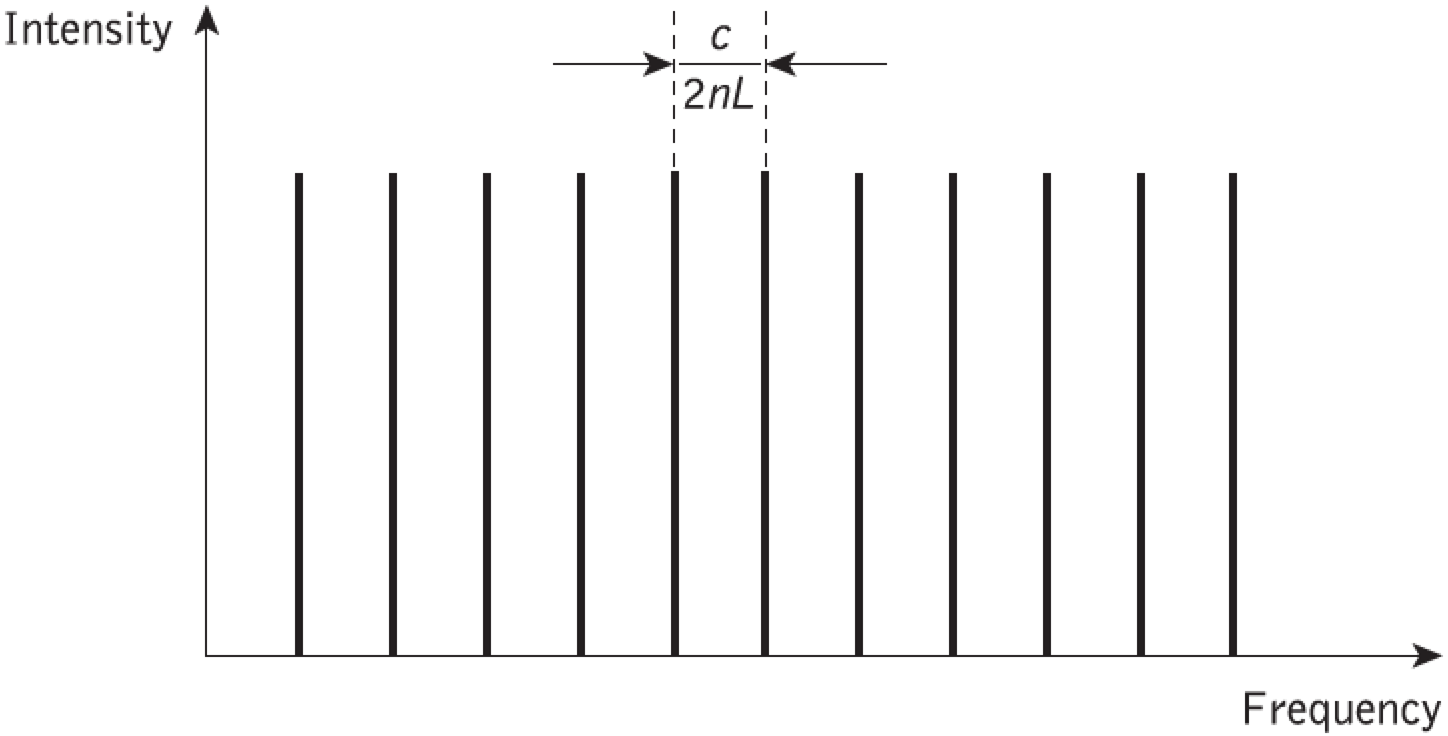
- When sufficient population inversion exists in the amplifying medium, the radiation builds up and becomes established as standing waves between the mirrors.
- These standing waves exist only at frequencies for which the distance between the mirrors is an integral number of half wavelengths. Thus when the optical spacing between the mirrors is *L*, the resonance condition along the axis of the cavity is

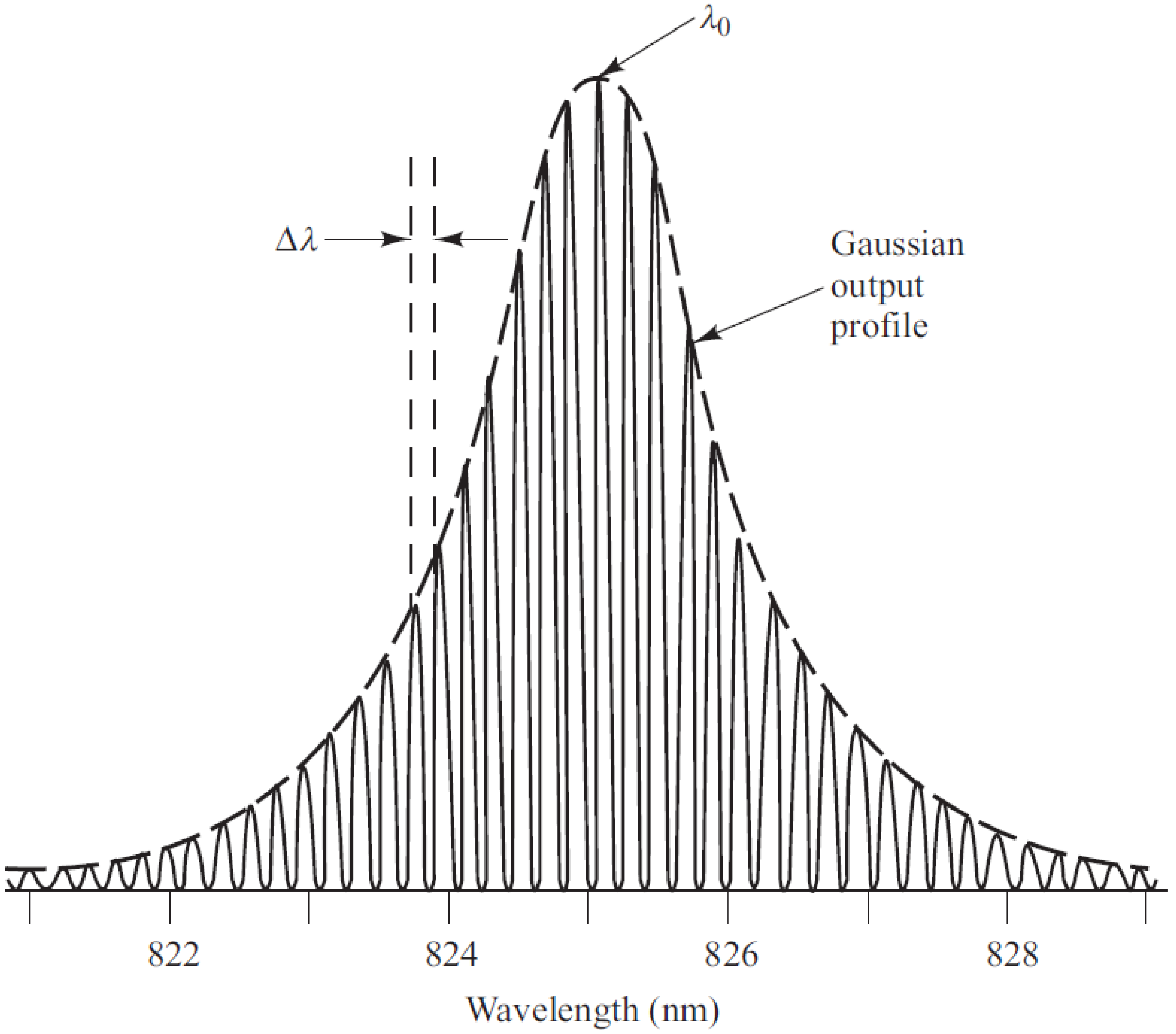
$$L = \frac{m\lambda}{2n}$$

- where λ is the emission wavelength, *n* is the refractive index of the amplifying medium and *m* is an integer.

$$f = \frac{mc}{2nL}$$

- The different frequencies of oscillation within the laser cavity are determined by the various integer values of *m* and each constitutes a resonance or mode.
- The modes are separated by a frequency interval $\delta f = \frac{c}{2nL}$ or $\delta\lambda = \frac{\lambda^2}{2nL}$


Intensity
$\frac{c}{2nL}$
Frequency

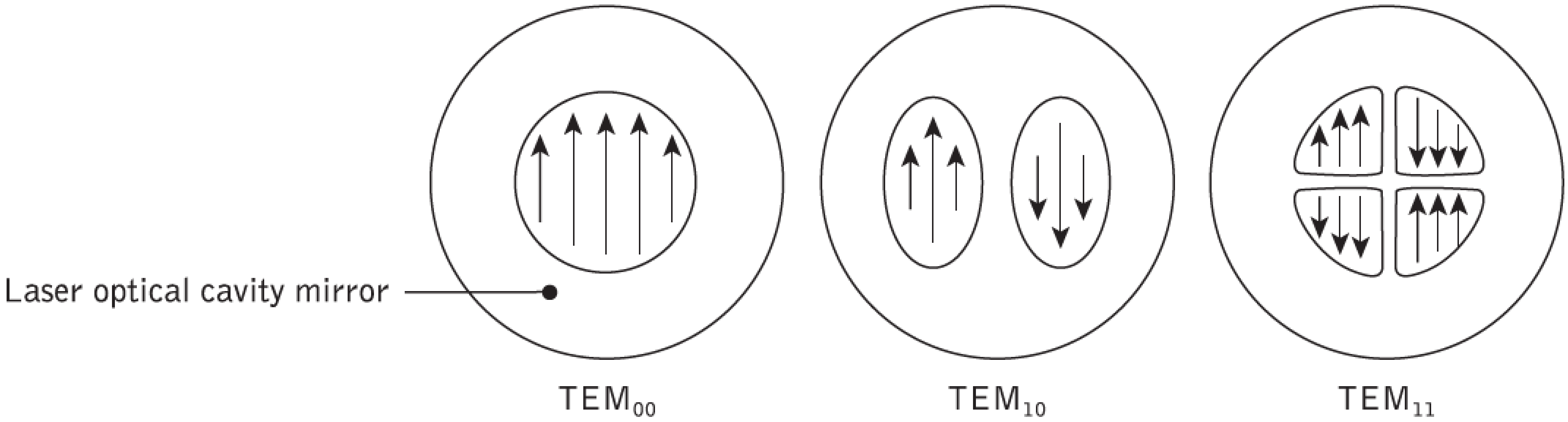


λ_0
$\Delta\lambda$
Gaussian
output
profile
822
824
826
828
Wavelength (nm)

Modes in Laser

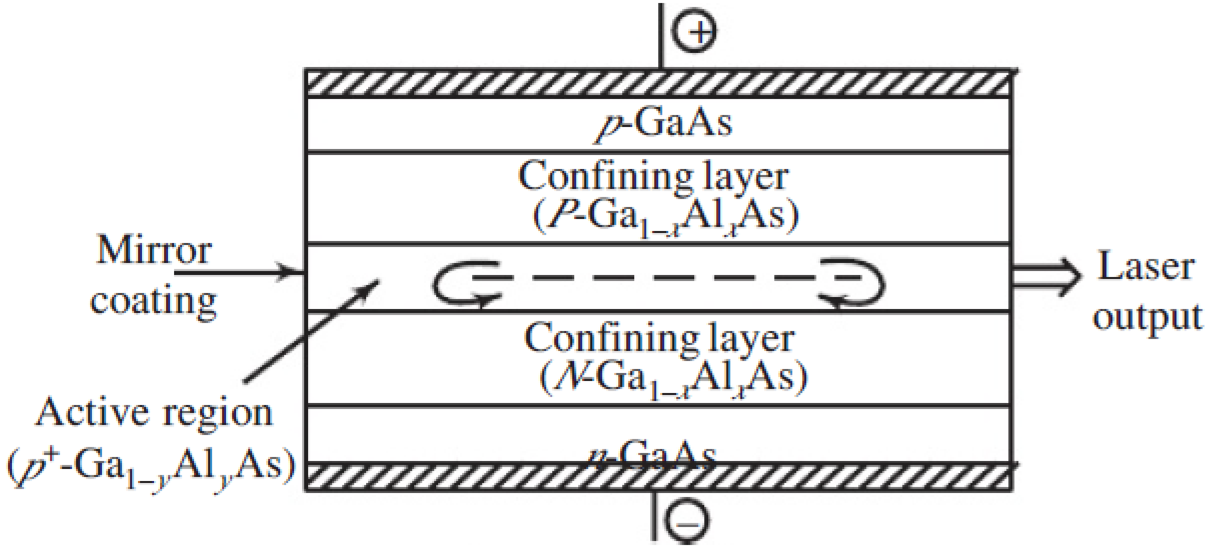
- The optical radiation within the resonance cavity of a laser diode sets up a pattern of electric and magnetic field lines called the modes of the cavity (sets of TE and TM modes).
- Each set of modes can be described in terms of the longitudinal, lateral, and transverse half-sinusoidal variations of the electromagnetic fields along the major axes of the cavity.
- The **longitudinal modes** are related to the **length of the cavity L** and determine the principal structure of the **frequency spectrum of the emitted optical radiation**. Since L is much larger than the lasing wavelength of approximately 1 mm, many longitudinal modes can exist.
- **Lateral modes** lie in the plane of the pn junction. These modes depend **on the side wall preparation and the width of the cavity**, and determine the **shape of the lateral profile of the laser beam**.
- **Transverse modes** are associated with the **electromagnetic field and beam profile in the direction perpendicular to the plane** of the pn junction. These modes are of great importance as they largely determine such **laser characteristics as the radiation and the threshold current density**.

- As the laser output consists of several modes is called a multimode laser. All these axial modes contribute to a single '**spot**' of light in the output.
- The resonant modes may be formed in a direction transverse to the axis of the cavity. These are called transverse electromagnetic (TEM) modes e.g., TEM_{lm}. Here, l and m give the number of minima as the output beam is scanned horizontally and vertically, respectively



LASER STRUCTURE

- Basic requirements for efficient operation of laser diodes
  - transverse optical confinement and carrier confinement between heterojunction layers,
  - the current flow must be restricted laterally to a narrow stripe along the length of the laser.



HETEROSTRUCTURE LASER DIODES

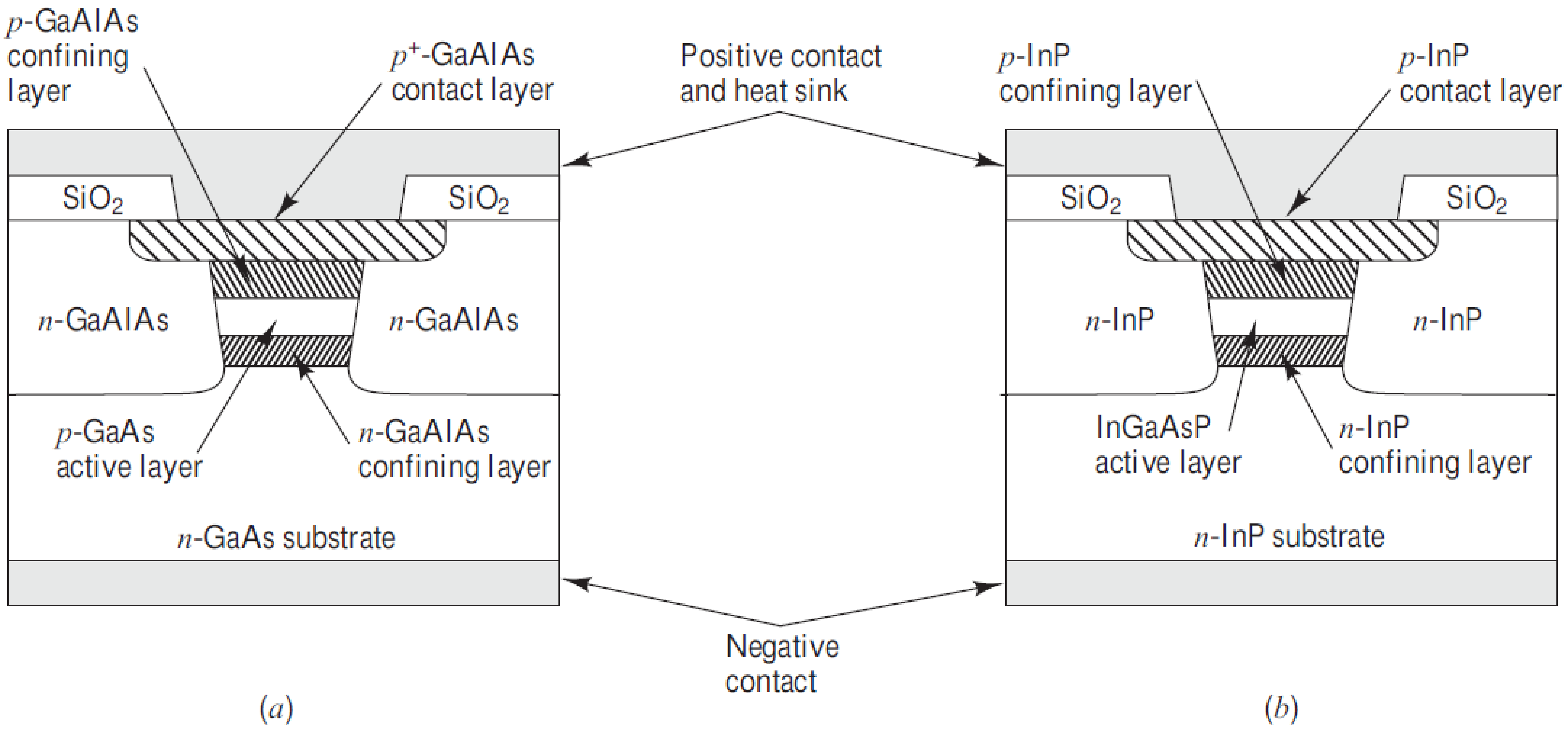
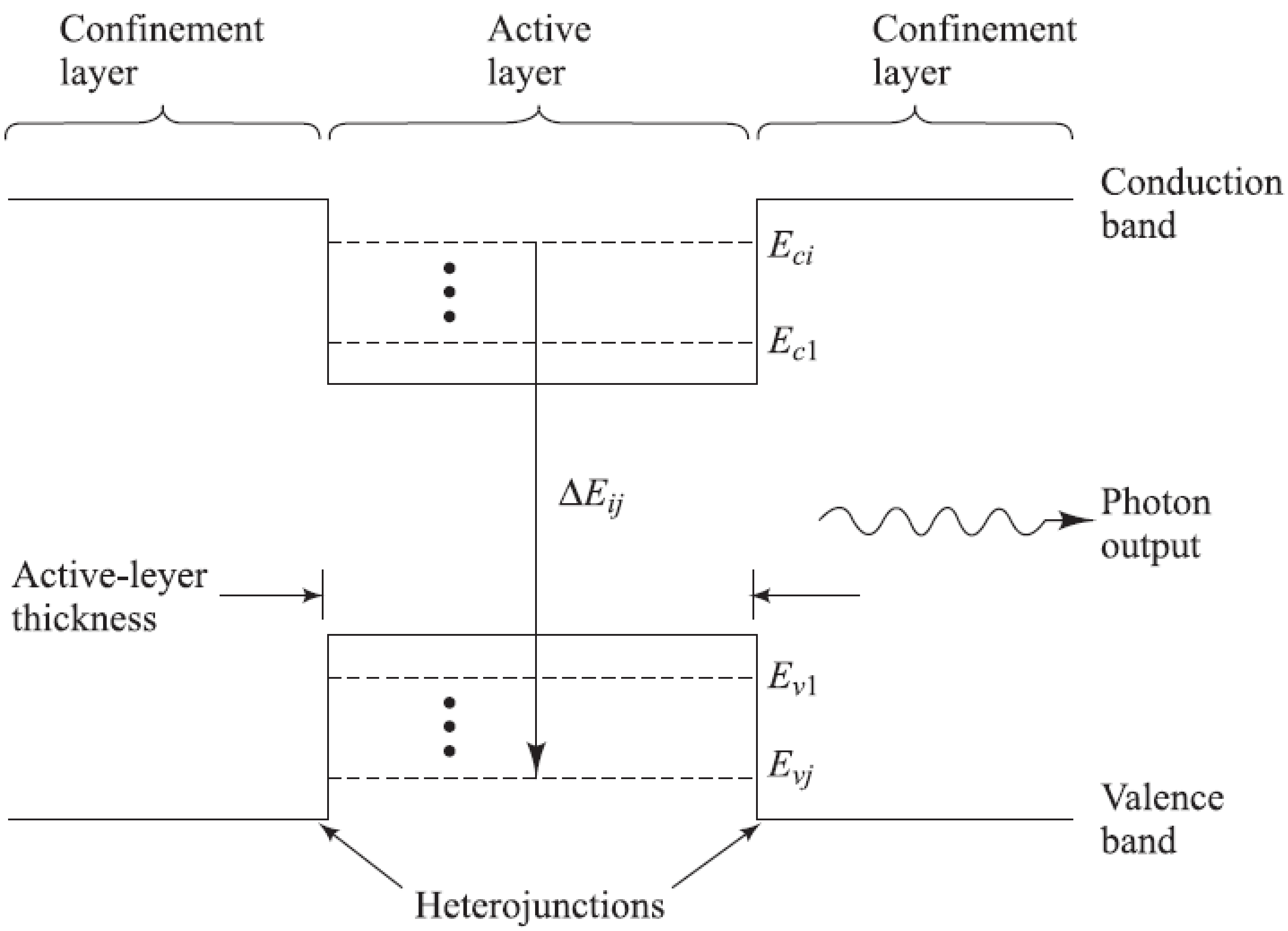
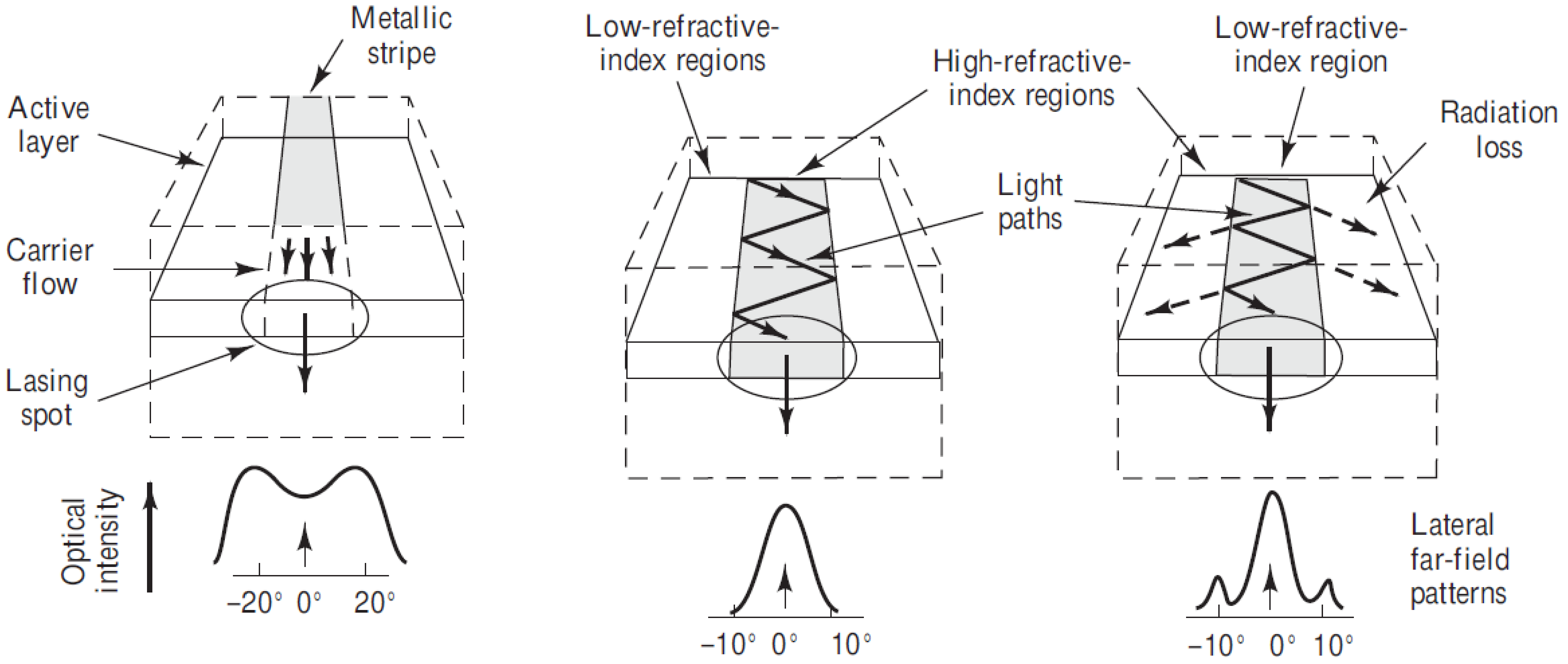


Fig: (a) Short-wavelength (800–900 nm) GaAlAs and (b) long-wavelength (1300–1600 nm) InGaAsP


Confinement layer
Active layer
Confinement layer
Conduction band
E_{ci}
E_{c1}
ΔE_{ij}
Photon output
Active-leyer thickness
E_{v1}
E_{vj}
Valence band
Heterojunctions



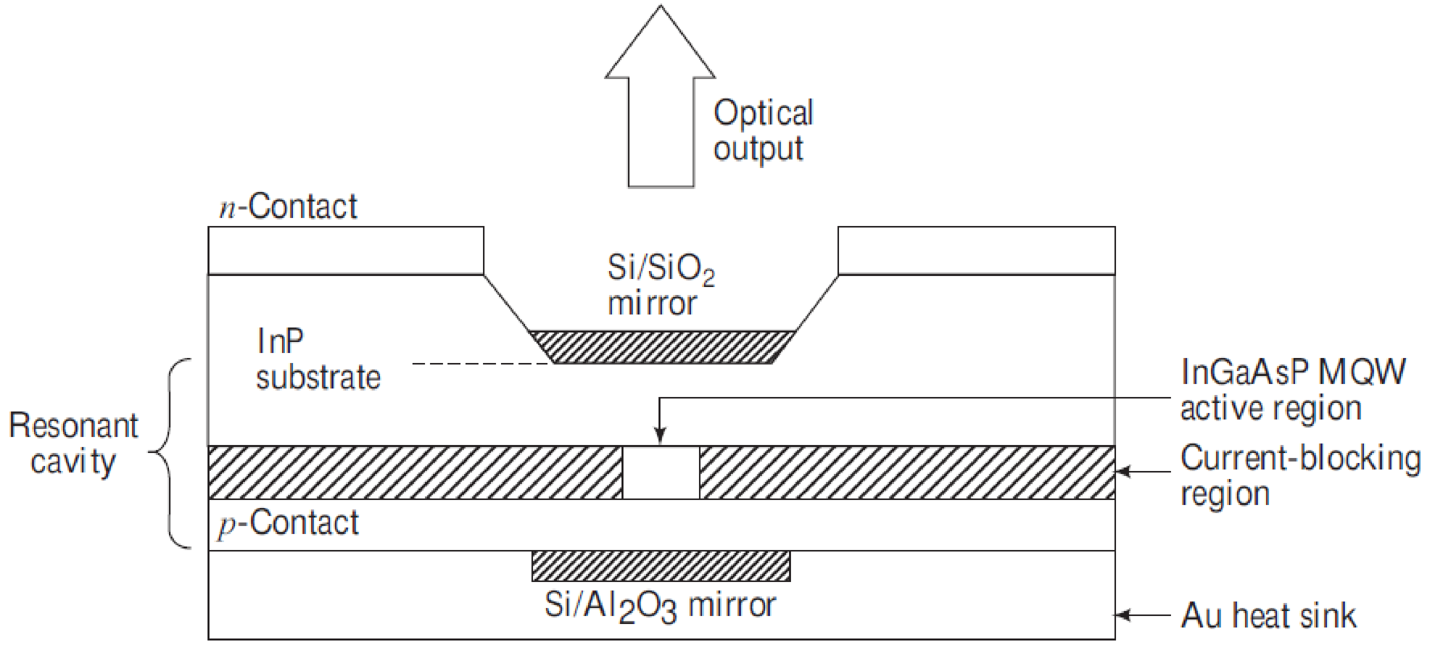
(a) in the gain-induced guide, electrons injected via a metallic stripe contact alter the index of refraction of the active layer;

(b) the positive index waveguide has a higher refractive index in the central portion of the active region;

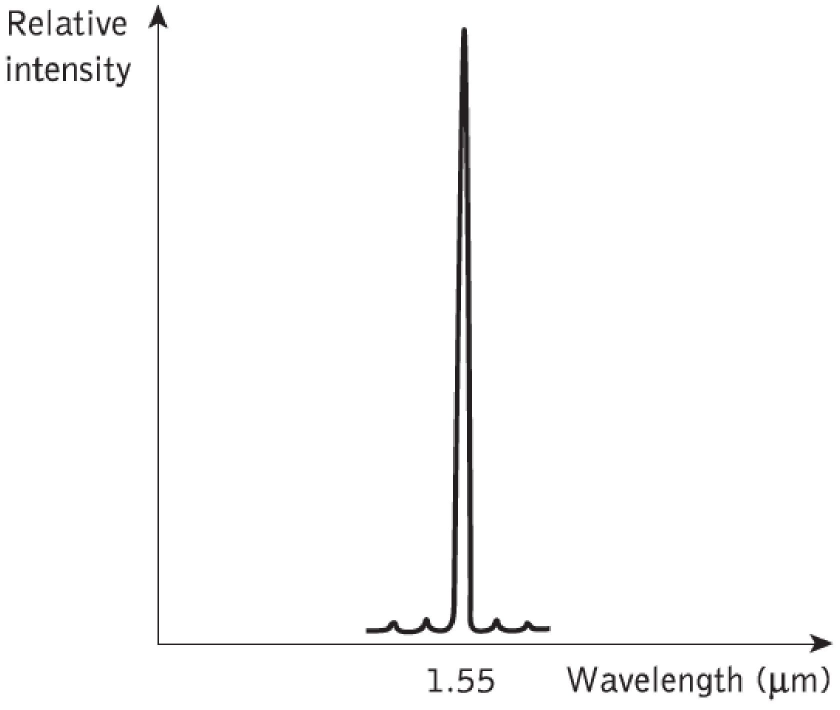
(c) the negative index waveguide has a lower refractive index in the central portion of the active region.

Single-Mode Lasers

- For high-speed long-distance communications one needs single-mode lasers, which must
  - contain only a single longitudinal mode and a single transverse mode.
  - the spectral width of the optical emission is very narrow.
- Method to achieve single longitudinal mode:
  - to reduce the length L of the lasing cavity to the point where the frequency separation of the adjacent modes is larger than the laser transition line width;
- For example, consider a Fabry-Perot cavity,
  - all longitudinal modes have nearly equal losses and are spaced by about 1 nm in a 250-mm-long cavity at 1300 nm.
  - By reducing L from 250 mm to 25 mm, the mode spacing increases from 1 nm to 10 nm. However, these lengths make the device hard to handle, and they are limited to optical output powers of only a few milliwatts



Basic architecture of a vertical-cavity surface-emitting laser (VCSEL)



- Light emission is perpendicular to the semiconductor surface
- The active-region volume of these devices is very small, which leads to very low threshold currents (< 100 mA).

External quantum efficiency

- Number of photons emitted per radiative electron-hole pair recombination above threshold, gives us the external quantum efficiency.

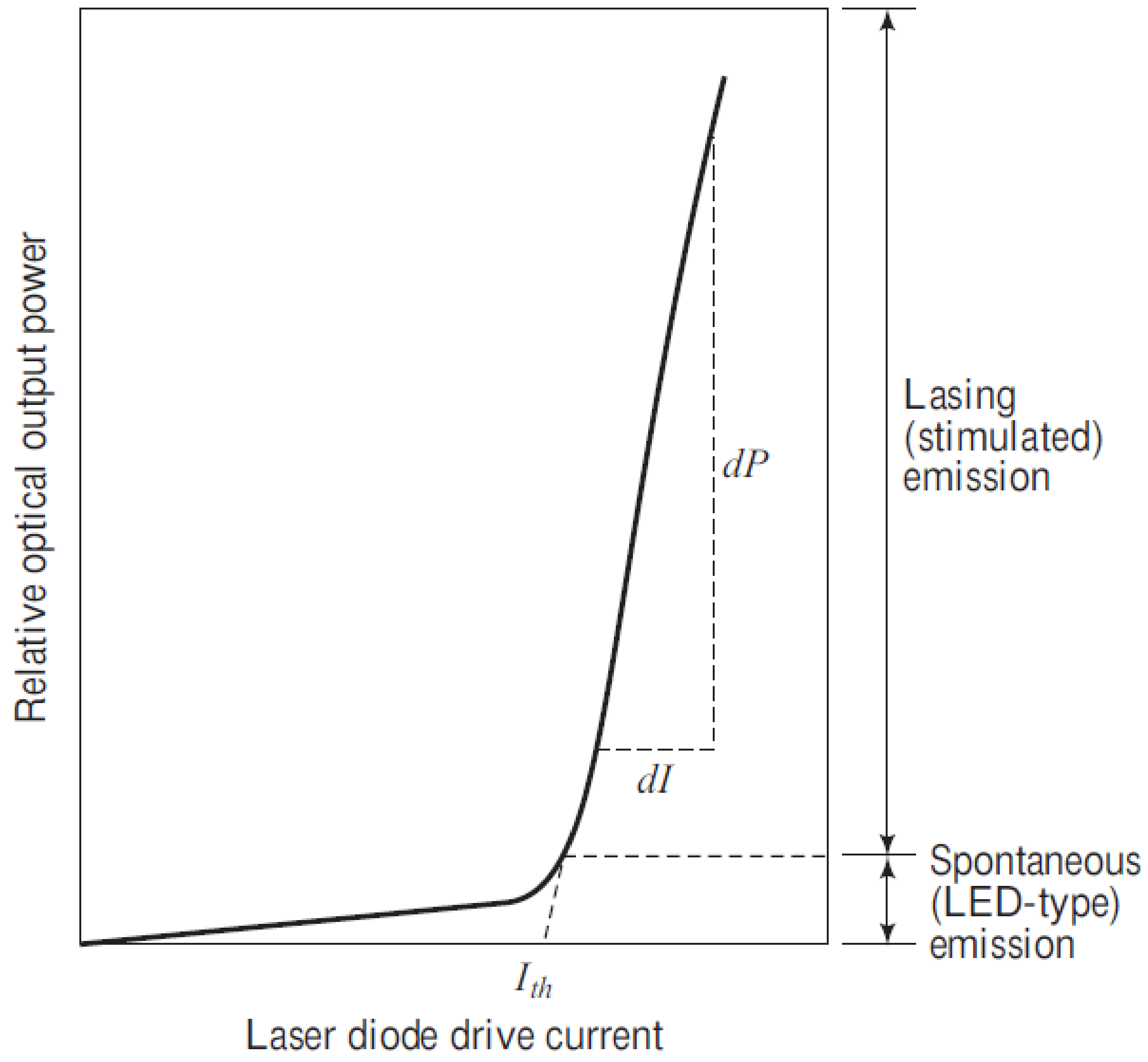
$$\eta_{ext} = \eta_{int} \frac{g_{th} - \alpha}{g_{th}}$$

- Typical values:

$$\eta_{int} \approx 60 \; to \; 70\%; \qquad \eta_{ext} \approx 15 \; to \; 40\%$$

- Experimentally, η_{ext} is calculated from the straight-line portion of the curve for the emitted optical power P versus drive current I

$$\eta_{ext} = \frac{q}{E_g} \frac{dP}{dI} = 0.8065\, \lambda\, (\mu m) \frac{dP\ (mW)}{dI\ (mA)}$$



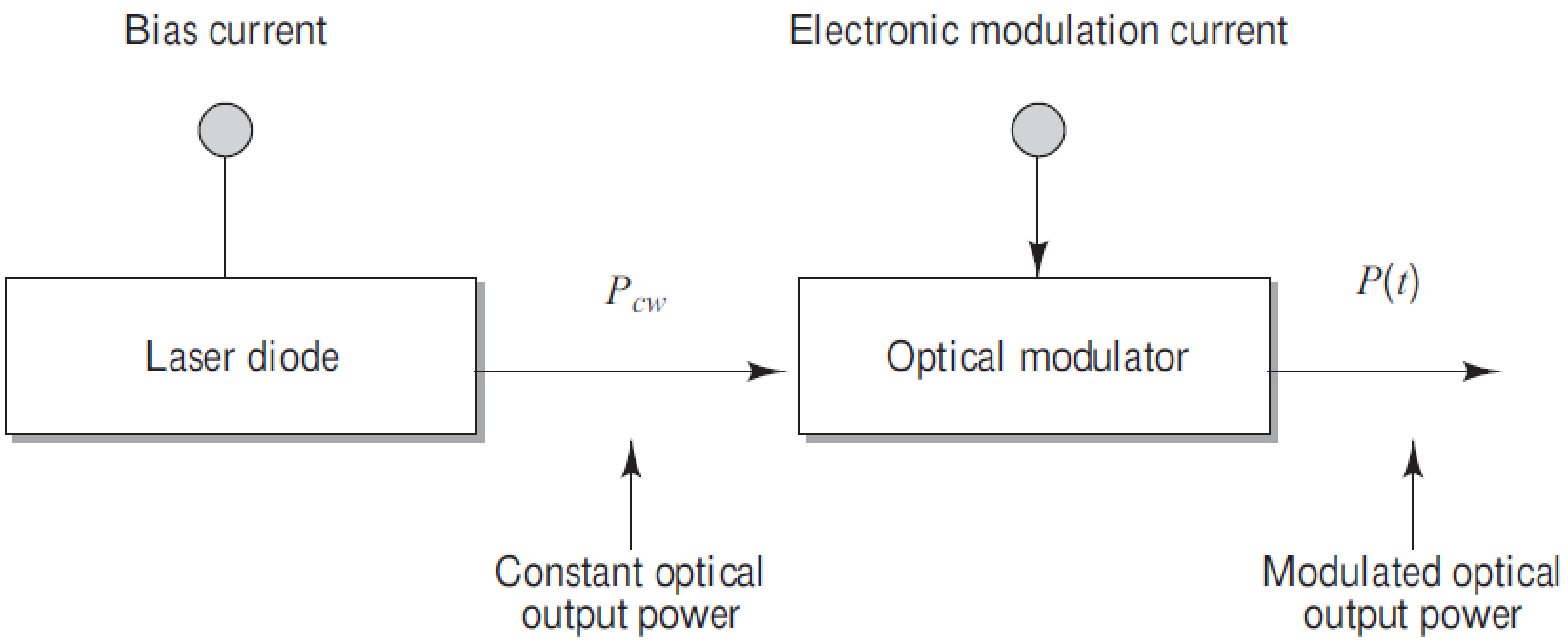
Relative optical output power
dP
dI
I_{th}
Laser diode drive current
Lasing (stimulated) emission
Spontaneous (LED-type) emission

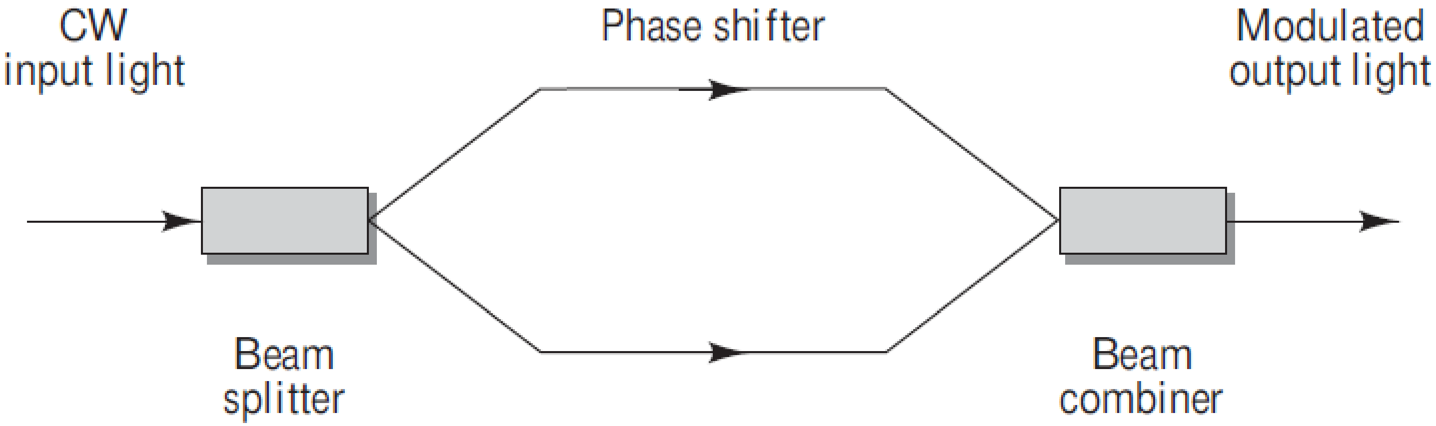
MODULATION OF LASER DIODES

- The process of putting information onto a light wave is called modulation.
- For data rates of less than approximately 10 Gb/s (typically 2.5 Gb/s), the process of imposing information on a laser-emitted light stream can be realized by **direct modulation**. This involves directly varying the laser drive current with the **electrically formatted information stream to produce a correspondingly varying optical output power**.
- The basic limitation on the direct modulation rate of laser diodes depends on the spontaneous and stimulated emission carrier lifetimes and the photon lifetime.
- When direct modulation is used in a laser transmitter, the process of turning the laser on and off with an electrical drive current produces a widening of the laser linewidth. This phenomenon is referred to as chirp and makes directly modulated lasers undesirable for operation at data rates greater than about 2.5 Gb/s.

MODULATION OF LASER DIODES

- For higher data rates one needs to use a device called an **external modulator** to temporally modify a steady optical power level emitted by the laser.
- A variety of external modulators are available commercially either as a separate device or as an integral part of the laser transmitter package.




CW
input light
Phase shifter
Modulated
output light
Beam
splitter
Beam
combiner

TEXT BOOKS

- Gerd Keiser, Optical Fiber Communications, TMH India, Fourth Edition, 2010.
- Senior John M., Optical Fiber Communications, Pearson Education India, Third Edition, 2009.
- R.P. Khare, *Fiber optics and optoelectronics, Oxford University Press 2004*