Satellite and Optical Communication

BEC515D

MODULE 5

Optical Sources and Detectors

Principles of Light-Emitting Diodes (LEDs)

Principles of Light-Emitting Diodes (LEDs)

- LEDs are preferred light sources for optical systems below **100–200 Mb/s**, offering **tens of microwatts** of multimode fiber-coupled power.
- They need **simpler drive circuits** than laser diodes, with **no thermal or optical stabilization**.
- Their **low cost** and **high fabrication yield** make them ideal for **moderate-speed optical links**.

LED Structures

- For use in fiber-optic communication, LEDs must provide **high radiance**, **fast response**, and **high quantum efficiency**.
- High radiance ensures sufficient optical power coupling into fibers, while fast emission response determines the modulation bandwidth.
- To achieve efficiency, LED designs confine both **charge carriers and optical fields** within the **active region** using **heterostructures**.
- The **double-heterostructure LED** is most effective—it traps carriers and light in a thin active layer, giving high efficiency and radiance.

LED Structures

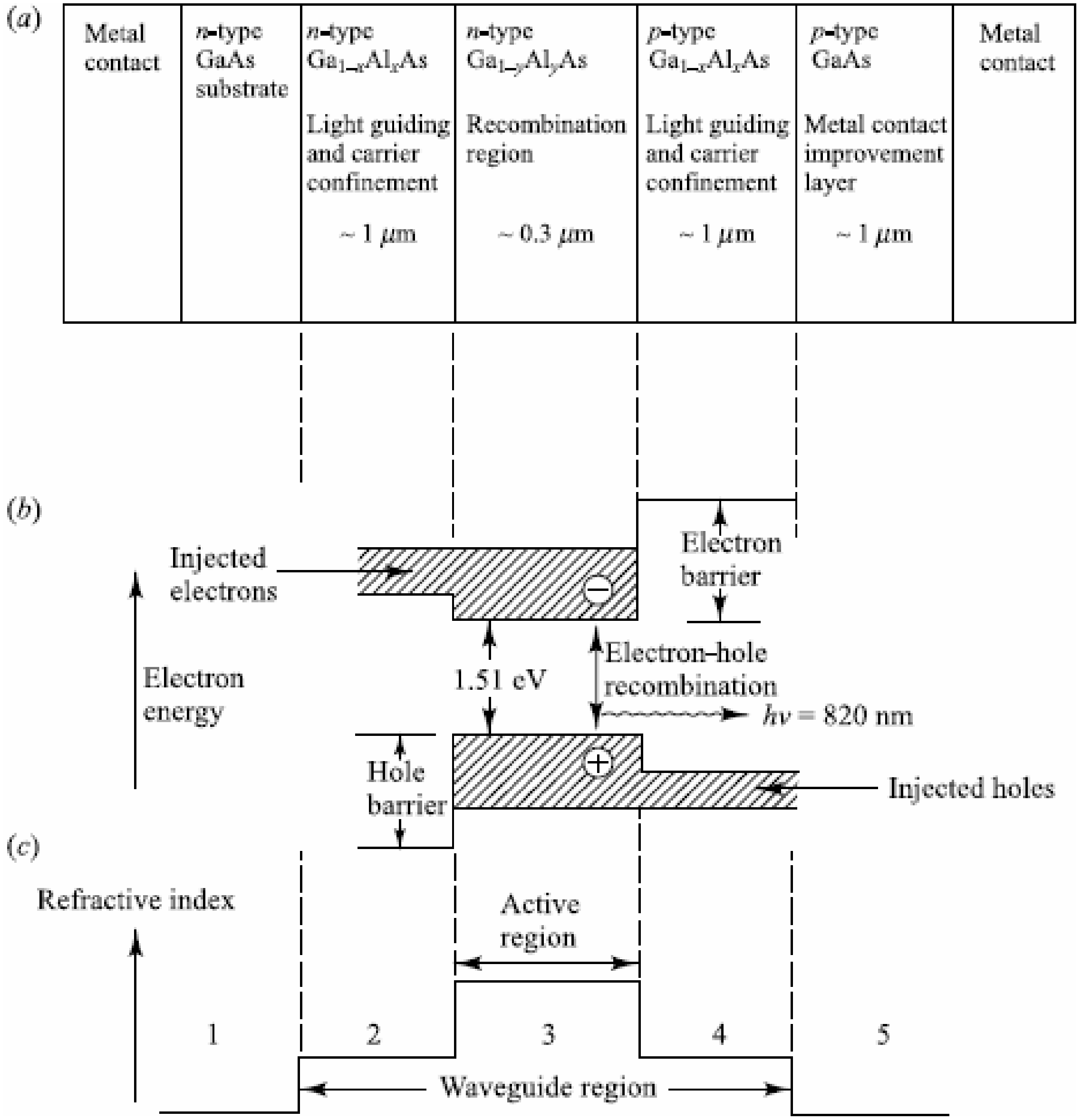


Fig. 4.8 **a** Cross-sectional drawing (not to scale) of a typical GaAlAs double-heterostructure light emitter in which x > y to provide for both carrier confinement and optical guiding; **b** energy band diagram showing the active region, and the electron and hole barriers that confine the charge carriers to the active layer; **c** variations in the refractive index; the lower index of refraction of the material in regions 1 and 5 creates an optical barrier around the waveguide region

LED Structures

- Two main configurations are used:
  - Surface emitters
  - Edge emitters
- Performance depends on factors like **optical absorption**, **interface recombination**, **doping**, **carrier density**, and **active-layer thickness**.

Surface Emitters

- Also known as Burrus or front emitters.
- The plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber.
- A well is etched through the substrate, allowing a fiber to be cemented directly to the active region to accept the light.
- The active area is typically 50 μm in diameter and up to 2.5 μm thick.
- This type is useful for coupling light into multimode fibers.

Surface Emitting LEDs

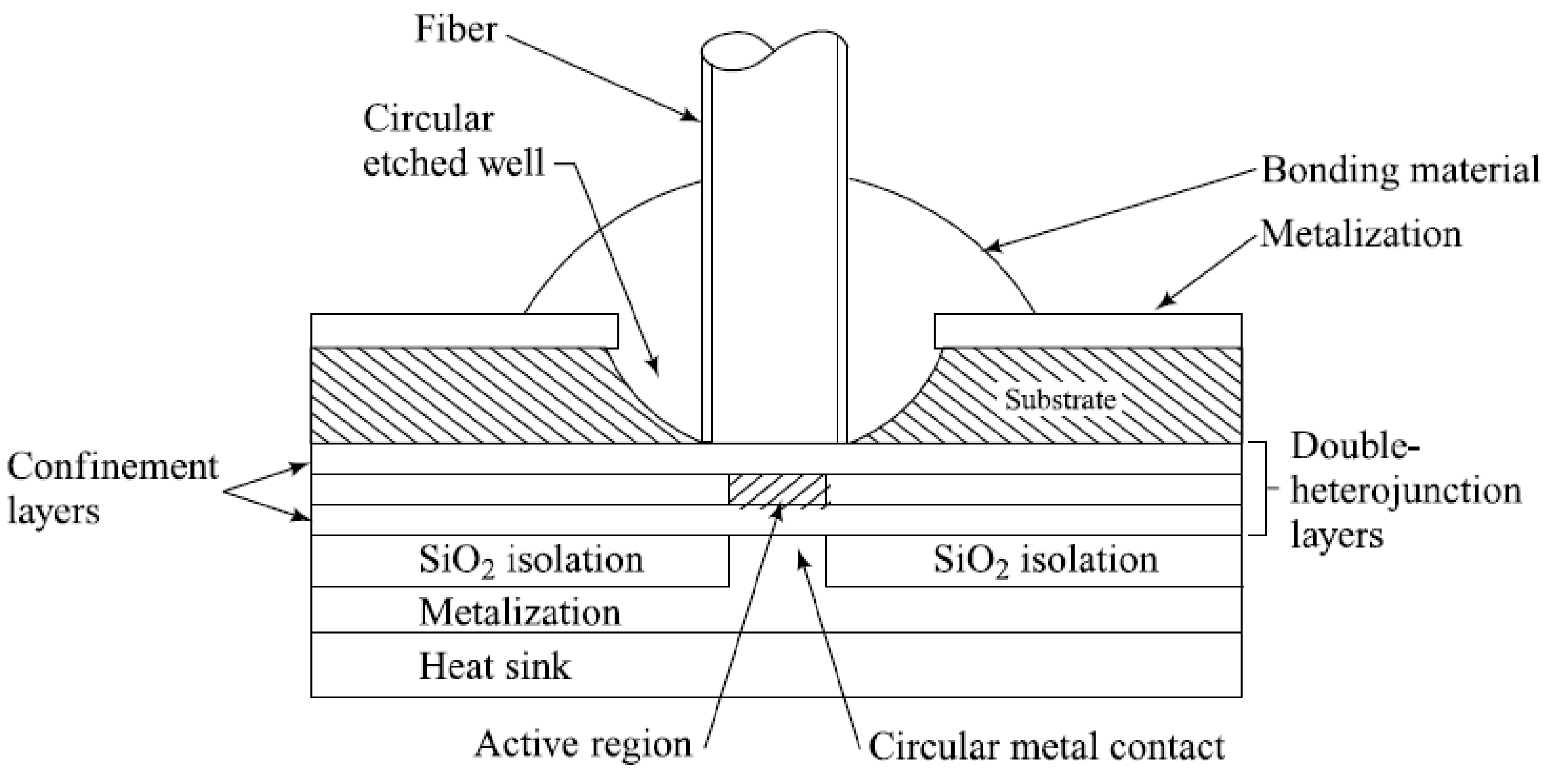


Fig. 4.9 Schematic (not to scale) of a high-radiance surface-emitting LED where the active region is limited to a circular section having an area compatible with the fiber-core end face

Surface Emitters

- The emission is isotropic (spreads in all directions), which is called a ***Lambertian pattern***.
- The source has the same apparent brightness (luminance) when viewed from any direction.
- Power diminishes as $\cos\theta$ where θ is the angle from the normal (the direction perpendicular to the surface).
- Power is at 50% when $\theta = 60°$, resulting in a total half-power beam width of $120°$.

Edge Emitters

- The light is emitted from the "edge" of the device.
- This type is composed of an active junction region (the light source) and two guiding layers.
- The guiding layers have a refractive index *lower* than the active region but *higher* than the surrounding material.
- This structure forms a waveguide channel.
- The waveguide directs the optical radiation toward the fiber core, resulting in a more focused beam.

Edge Emitters

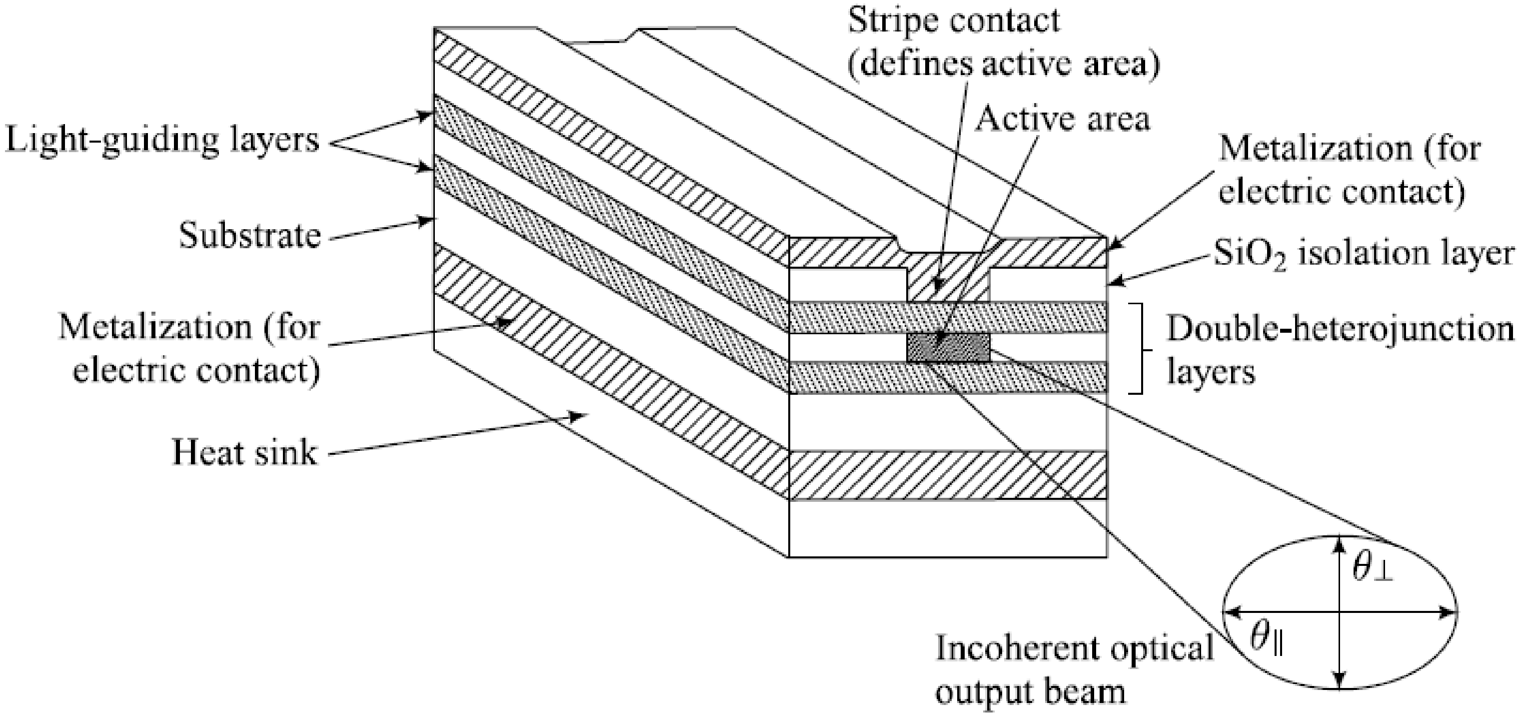
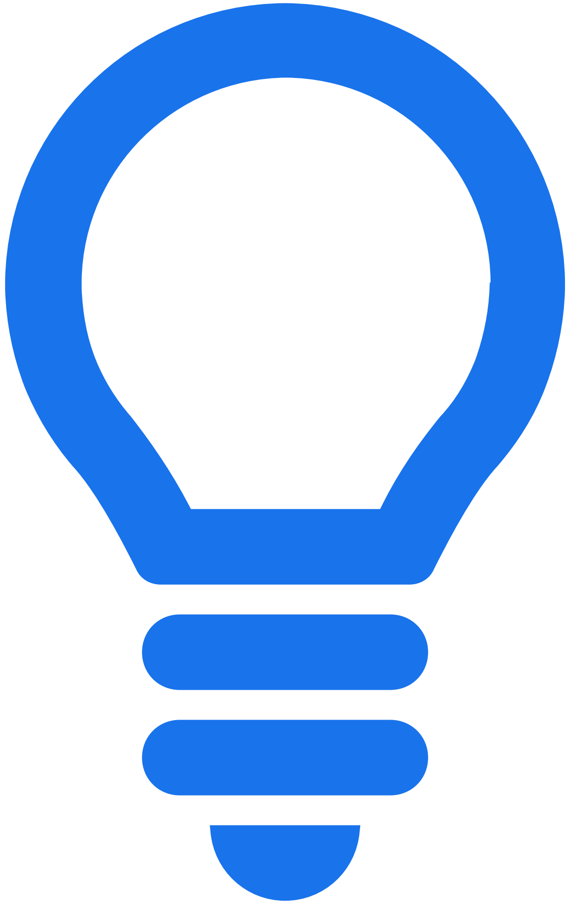


Fig. 4.10 Schematic (not to scale) of an edge-emitting double-heterojunction LED in which the output beam is Lambertian in the plane of the pn junction ($\theta_{||} = 120°$) and highly directional perpendicular to the pn junction ($\theta_\perp \approx 30°$)

Edge Emitters

- Contact stripes are 50–70 μm wide to match multimode fiber cores.
- Active region lengths are typically 100–150 μm.
- The emission pattern is more **directional** than the surface emitter and is asymmetrical:
  - **Parallel to Junction ($\boldsymbol{\theta}_{\parallel}$)** : The beam is Lambertian, with a wide half-power width of 120°.
  - **Perpendicular to Junction ($\boldsymbol{\theta}_{\perp}$) :** The waveguide effect narrows the beam significantly, with a half-power width of only 25°–35°.

Semiconductor Materials for Light Sources



Semiconductor Materials for Light Sources

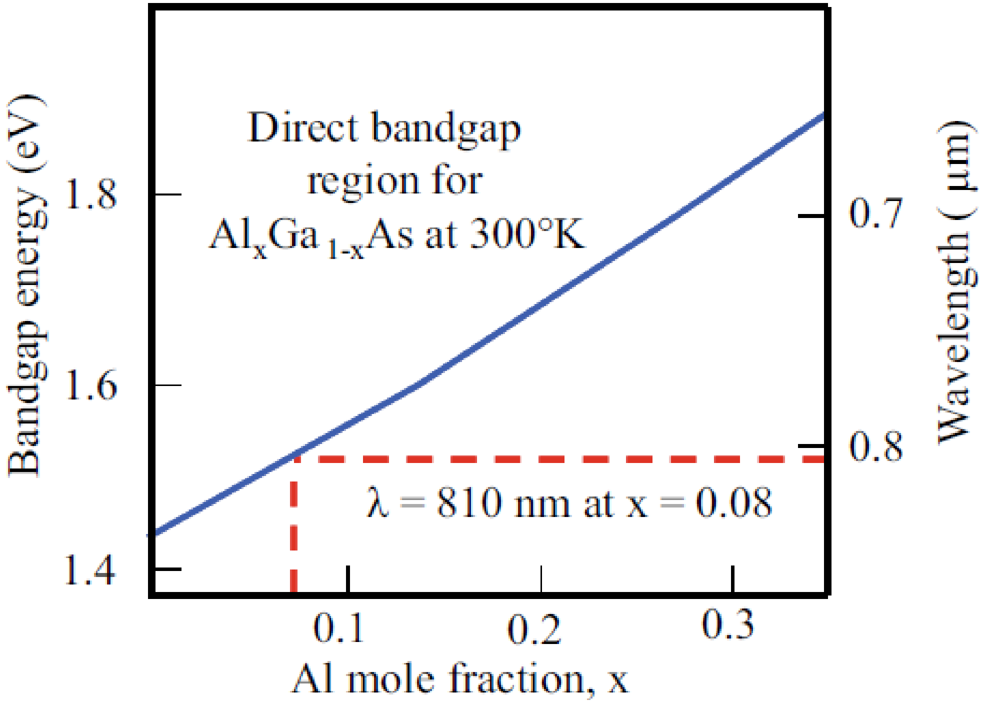
- The semiconductor material used for an optical source's active layer must have a direct bandgap.
- In a direct-bandgap material, electrons and holes recombine directly across the bandgap.
  - This process does not require a third particle to conserve momentum.
  - This direct recombination produces a high level of radiative efficiency and optical emission.
- Single-element semiconductors (like silicon) are not direct-bandgap, but compounds are.
- The most important of these compounds are made from III-V materials.
  - That is, the compounds consist of selections from a group III element (e.g., Al, Ga, or In) and a group V element (e.g., P, As, or Sb).
  - GaAlAs (Gallium Aluminium Arsenide) - Material for 800-900 nm
  - InGaAsP (Indium Gallium Arsenide Phospide) - Material for 1.0-1.7 μm

GaAlAs - Material for 800-900 nm

- The principal material for this spectrum is the ternary alloy $Ga_{1-x}Al_xAs$.
- The ratio x (aluminum arsenide to gallium arsenide) determines the bandgap and the peak emission wavelength.
- The bandgap changes from direct to indirect for values of $x > \mathbf{0.37}$.
- For 800-850 nm emission, x is typically chosen to be around 0.1.
- Example: For $x = \mathbf{0.08}$, the peak output power occurs at 810 nm.

GaAlAs – Material for 800-900 nm

Fig. 4.11 Bandgap energy and output wavelength as a function of aluminum mole fraction x for $Al_xGa_{1-x}As$ at room temperature



GaAlAs - Material for 800-900 nm

- The 810 nm $Ga_{1-x}Al_xAs$ LED $(x = 0.08)$ has an FWHM spectral width (σ_λ) of 36 nm.
- Full-Width Half-Maximum (FWHM) is the width of the spectral pattern at its half-power point.
  - For LEDs, this parameter typically varies between 20 and 50 nm.

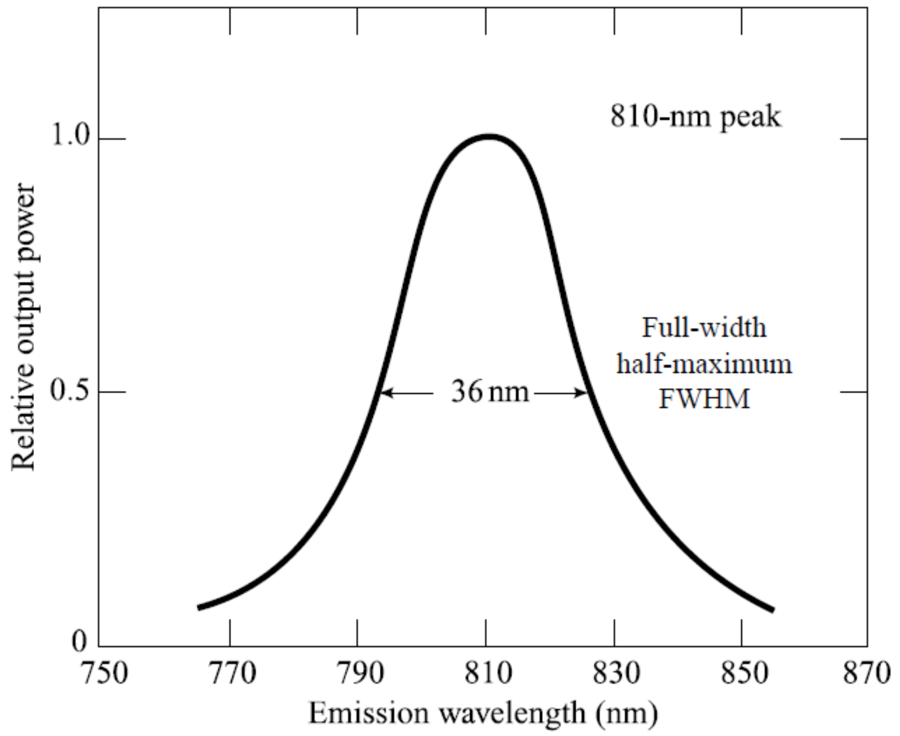


Fig. 4.12 Spectral emission pattern of a representative 810-nm $Ga_{1-x}Al_xAs$ LED with x = 0.08, which gives a spectral pattern width at its half-power point of 36 nm

InGaAsP – Material for 1.0–1.7 μm

- For longer wavelengths, the quaternary alloy $In_{1-x}Ga_xAs_yP_{1-y}$ is a primary candidate.
- By varying the mole fractions x and y, LEDs can be constructed with peak output at any wavelength between 1.0 and 1.7 μm (1000–1700 nm).
- This material is often simplified to InGaAsP.

Semiconductor Materials for Light Sources

- **GaAlAs** and **InGaAsP** are used because they allow for lattice matching at heterostructure interfaces.
- A **heterojunction** joins two materials with the same lattice constant but *different* bandgap energies.
- This close lattice match is required to:
  - Reduce interfacial defects.
  - Minimize strain from temperature changes.
  - Improve radiative efficiency and device lifetime.
- The bandgap differences are used to confine the charge carriers.

Semiconductor Materials for Light Sources

- The peak emission wavelength λ is determined by the bandgap energy (E_g).
- The fundamental relationship is $E = h\nu = hc/\lambda$.
- This gives the practical equation:

$$\lambda(\text{in } \mu\text{m}) = \frac{1.240}{E_g(\text{in eV})}$$

Semiconductor Materials for Light Sources

Table 4.1 Bandgap energies of some common semiconductor materials

Semiconductor material	Bandgap energy (eV)
Silicon (Si)	1.12
GaAs	1.43
Germanium (Ge)	0.67
InP	1.35
$Ga_{0.93}Al_{0.07}As$	1.51
$In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$	0.97

Calculating Bandgap Energy (E_g)

- For $Ga_{1-x}Al_xAs$ (in the direct-bandgap region, $x < 0.37$):

$$E_g = 1.424 + 1.266x + 0.266x^2$$

- For $In_{1-x}Ga_xAs_yP_{1-y}$ (lattice-matched to InP, with $y = 2.20x$ and $0 \le x \le 0.47$):

$$E_g = 1.35 - 0.72y + 0.12y^2$$

(This system covers wavelengths from 0.92 to 1.65 μm)

Example 4.3 A particular $Ga_{1-x}Al_xAs$ laser is constructed with a material ratio $x = 0.07$. Find (*a*) the bandgap of this material; (*b*) the peak emission wavelength.

Solution:

Given $x = 0.07$

(a) Bandgap energy is given by

$$E_g = 1.424 + 1.266x + 0.266x^2$$

$$E_g = 1.424 + 1.266(0.07) + 0.266(0.07)^2$$

$$E_g = 1.51\ eV$$

Example 4.3 A particular $Ga_{1-x}Al_xAs$ laser is constructed with a material ratio $x = 0.07$. Find (*a*) the bandgap of this material; (*b*) the peak emission wavelength.

(b) Peak emission wavelength is given by

$$\lambda(\text{in } \mu\text{m}) = \frac{1.240}{E_g(\text{in eV})}$$

$$= \frac{1.240}{1.51}$$

$$= 0.82\ \mu\text{m}$$

$$\lambda = 820\ nm$$

Example 4.4 Consider the material alloy $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, that is, $x = 0.26$ and $y = 0.57$ in the general formula $In_{1-x}Ga_xAs_yP_{1-y}$. Find (*a*) the bandgap of this material; (*b*) the peak emission wavelength.

Solution:

Given $x = 0.26$, $y = 0.57$

(a) Bandgap energy is given by

$$E_g = 1.35 - 0.72y + 0.12y^2$$

$$E_g = 1.35 - 0.72(0.57) + 0.12(0.57)^2$$

$$E_g = 0.97\ eV$$

Example 4.4 Consider the material alloy $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, that is, $x = 0.26$ and $y = 0.57$ in the general formula $In_{1-x}Ga_xAs_yP_{1-y}$. Find (*a*) the bandgap of this material; (*b*) the peak emission wavelength.

(b) Peak emission wavelength is given by

$$\lambda(\text{in } \mu\text{m}) = \frac{1.240}{E_g(\text{in eV})}$$

$$= \frac{1.240}{0.97}$$

$$= 1.27\ \mu\text{m}$$

$$\lambda = 1270\ nm$$

Spectral Width Comparisons

- FWHM spectral widths are wider at longer wavelengths.
  - **800 nm region:** ~35 nm
  - **1300–1600 nm region:** 70 to 180 nm
- Device Type:
  - **Surface-emitting LEDs (SLEDs)** tend to have *broader* spectral widths.
  - **Edge-emitting LEDs (ELEDs)** have *narrower* spectral widths.
- This is due to different internal absorption effects in the device structures.

Spectral Width Comparisons

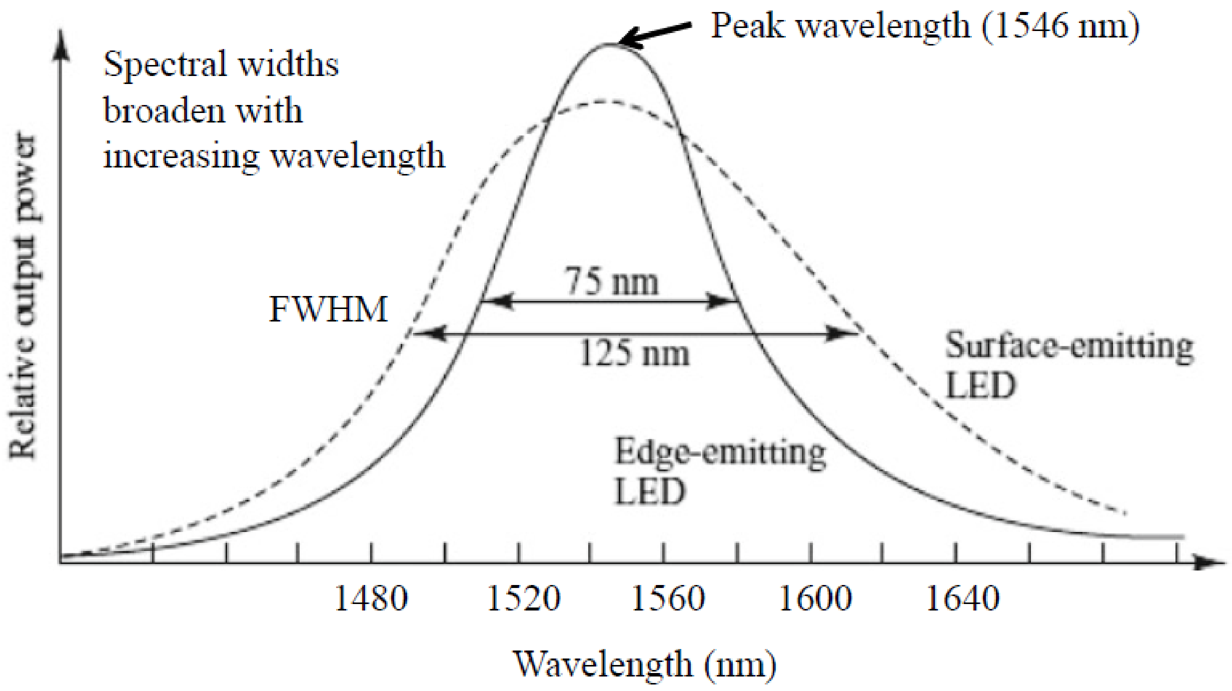
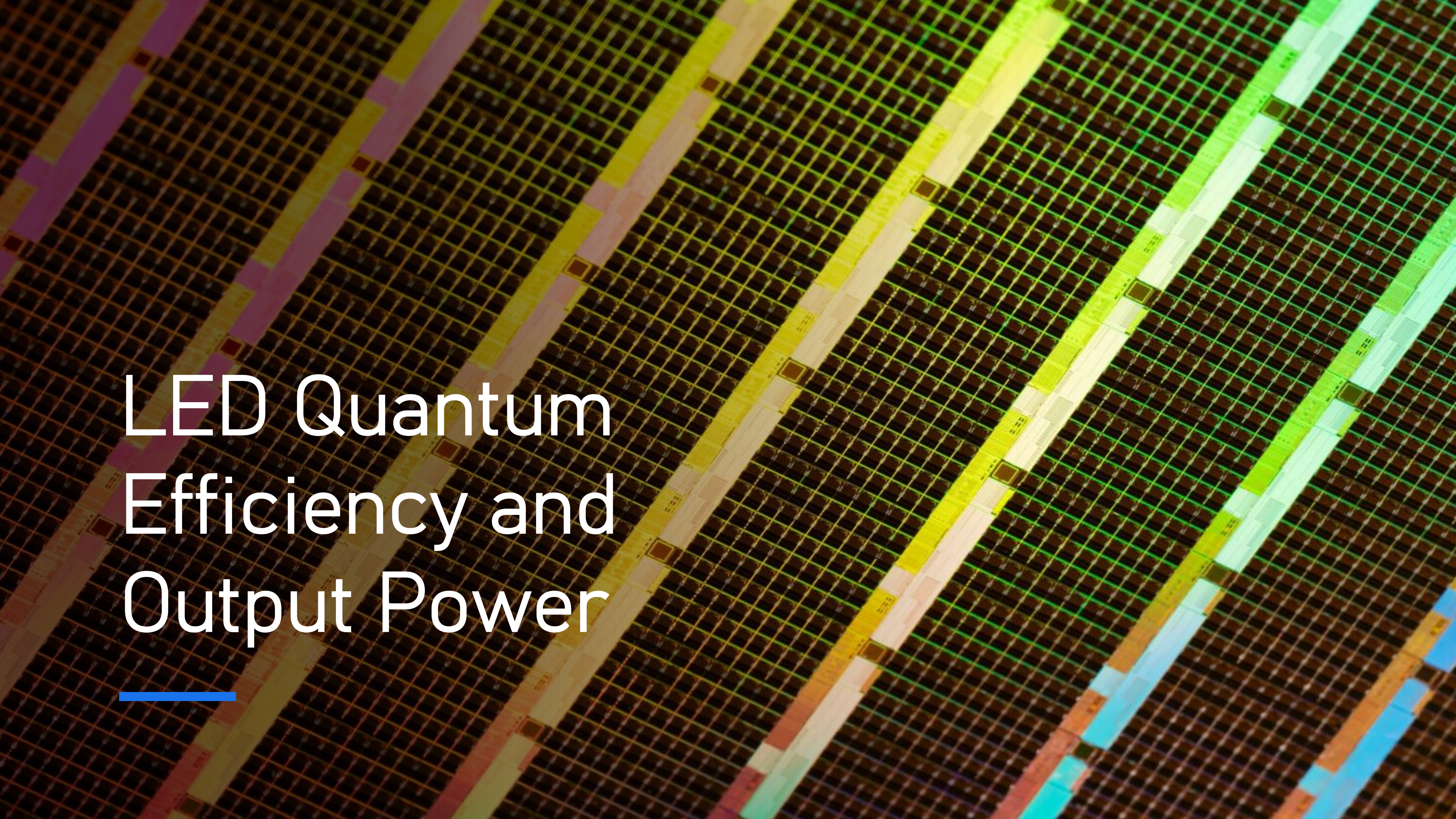


Fig. 4.13 Typical spectral patterns for edge-emitting and surface-emitting LEDs at 1310 nm. The patterns broaden with increasing wavelength and are wider for surface emitters

Typical LED Characteristics

Table 4.2 Typical characteristics of surface-emitting and edge-emitting LEDs

LED type	Material	Wavelength (nm)	Operating current (mA)	Fiber-coupled power (μW)	Nominal FWHM (nm)
SLED	GaAlAs	850	110	40	35
ELED	InGaAsP	1310	100	15	80
SLED	InGaAsP	1310	110	30	150



LED Quantum Efficiency and Output Power

Minority Carriers and Lifetime

- An excess of electrons and holes in p-type and n-type material, respectively (referred to as minority carriers) is created in a semiconductor light source by carrier injection at the device contacts.
- When carrier injection stops, the carrier density returns to the equilibrium value.
- In general, the excess carrier density decays exponentially with time according to the relation

$$n = n_0 e^{-t/\tau}$$

where n_0 is the initial injected excess electron density and the time constant τ is the carrier lifetime (the average time it takes for a minority carrier to recombine).

Radiative vs. Nonradiative Recombination

- The excess carriers can recombine either radiatively or nonradiatively.
- **Radiative Recombination:** An electron-hole pair recombines, emitting a photon with energy $h\nu \approx E_g$ (bandgap energy).
- **Nonradiative Recombination:** Energy is lost without emitting a photon.
  - Mechanisms include
    - Optical absorption in the active region (self-absorption)
    - Carrier recombination at the heterostructure interfaces
    - *Auger process* in which the energy released during an electron-hole recombination is transferred to another carrier in the form of kinetic energy.

Steady-State Carrier Density

- With a constant current I (current density J), an equilibrium is established.
- Then the rate equation for carrier recombination in an LED can be written as

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau}$$

- At equilibrium $\left(\frac{dn}{dt} = 0\right)$,the steady-state electron density is:

$$n = \frac{J\tau}{qd}$$

Internal Quantum Efficiency

- Internal Quantum Efficiency (η_{int}) is the fraction of electron-hole pairs that recombine radiatively.
- If the radiative recombination rate is R_r and the nonradiative recombination rate is R_{nr}, then the internal quantum efficiency η_{int} is the ratio of the radiative recombination rate to the total recombination rate:

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$

Internal Quantum Efficiency

- For exponential decay of excess carriers, the radiative recombination lifetime is $\tau_r = n/R_r$ and the nonradiative recombination lifetime is $\tau_{nr} = n/R_{nr}$.
- Thus the internal quantum efficiency can be expressed as

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}} = \frac{\tau}{\tau_r}$$

where the *bulk recombination lifetime* τ is

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Internal Quantum Efficiency

- For direct-bandgap materials, τ_r and τ_{nr} are often comparable.
- Simple homojunction LEDs have $\eta_{int} \approx 50\%$.
- Double-heterojunction LEDs can achieve η_{int} of 60 to 80%.
    - This is due to thin active regions that confine carriers and reduce self-absorption (a nonradiative process).

Internal Optical Power ($\boldsymbol{P_{int}}$)

- If the current injected into the LED is I, then the total number of recombinations per second is

$$R_r + R_{nr} = I/\mathrm{q}$$

- The number of photons generated per second is $R_r = \eta_{int}(I/\mathrm{q})$
- Since each photon has energy $h\upsilon = hc/\lambda$, the internally generated optical power is:

$$P_{int} = \eta_{int}\frac{I}{q}h\nu = \eta_{int}\frac{hcI}{q\lambda}$$

Example 4.5 Suppose that a double-heterojunction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 30 and 100 ns, respectively, and let the drive current be 40 mA. Find (*a*) the bulk recombination time; (*b*) the internal quantum efficiency; and (*c*) the internal power level.

Solution:

Given $\lambda = 1310\ nm$, $\tau_r = 30\ ns$, $\tau_{nr} = 100\ ns$, $I = 40\ mA$

(a) The bulk recombination lifetime is

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}}$$

$$= \frac{30 \times 300}{30 + 300}\ \text{ns}$$

$$= 23.1\ \text{ns}$$

Example 4.5 Suppose that a double-heterojunction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 30 and 100 ns, respectively, and let the drive current be 40 mA. Find (*a*) the bulk recombination time; (*b*) the internal quantum efficiency; and (*c*) the internal power level.

(b) The internal quantum efficiency is

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.1}{30} = 0.77$$

Example 4.5 Suppose that a double-heterojunction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 30 and 100 ns, respectively, and let the drive current be 40 mA. Find (*a*) the bulk recombination time; (*b*) the internal quantum efficiency; and (*c*) the internal power level.

(c) The internal power level is

$$P_{int} = \eta_{int}\frac{hcI}{q\lambda}$$

$$= 0.77\frac{(6.6256 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m/s})(0.040\ \text{A})}{(1.602 \times 10^{-19}\ \text{C})(1.31 \times 10^{-6}\ \text{m})}$$

$$= 29.2\,\text{mW}$$

External Quantum Efficiency

- Not all internally generated photons escape the device.
- Light only escapes if it strikes the surface within the critical angle ϕ_c.
- $\phi_c = \sin^{-1}(n_2/n_1)$. Here, n_1 is the refractive index of the semiconductor material and n_2 is the refractive index of the outside material, which nominally is air with $n_2 = 1.0$.
- Light outside this cone suffers Total Internal Reflection (TIR) and is trapped.

External Quantum Efficiency

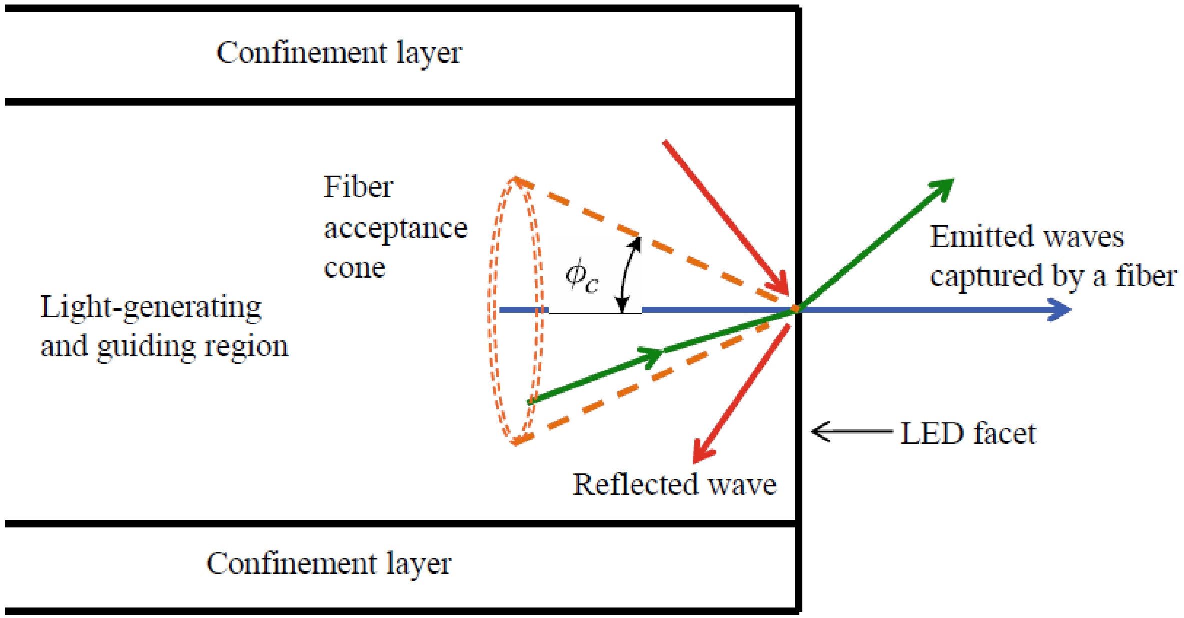


Fig. 4.14 Only light emitted from an optical source that falls within an acceptance cone defined by the critical angle φ_c will be captured by the fiber

External Quantum Efficiency

- The external quantum efficiency can then be calculated from the expression

$$\eta_{ext} = \frac{1}{4\pi} \int_0^{\phi_c} T(\phi)(2\pi \sin\phi) d\phi$$

- where $T(\phi)$ is the *Fresnel transmission coefficient* or *Fresnel transmissivity*.
- This factor depends on the incidence angle ϕ, but, for simplicity, we can use the expression for normal incidence,

$$T(0) = \frac{4n_1 n_2}{(n_1 + n_2)^2}$$

External Quantum Efficiency

- Assuming the outside medium is air and letting $n_1 = n$, then $T(0) = \frac{4n}{(n+1)^2}$.
- The external quantum efficiency is then approximately given by

$$\eta_{ext} = \frac{1}{n(n+1)^2}$$

Emitted Optical Power (P)

- The final optical power emitted from the LED is the internal power reduced by the external quantum efficiency.

$$P = \eta_{ext} P_{int} = \frac{P_{int}}{n(n+1)^2}$$

Example 4.6 Assume a typical value of $n = 3.5$ for the refractive index of an LED material. What percent of the internally generated optical power is emitted into an air medium?

Solution:

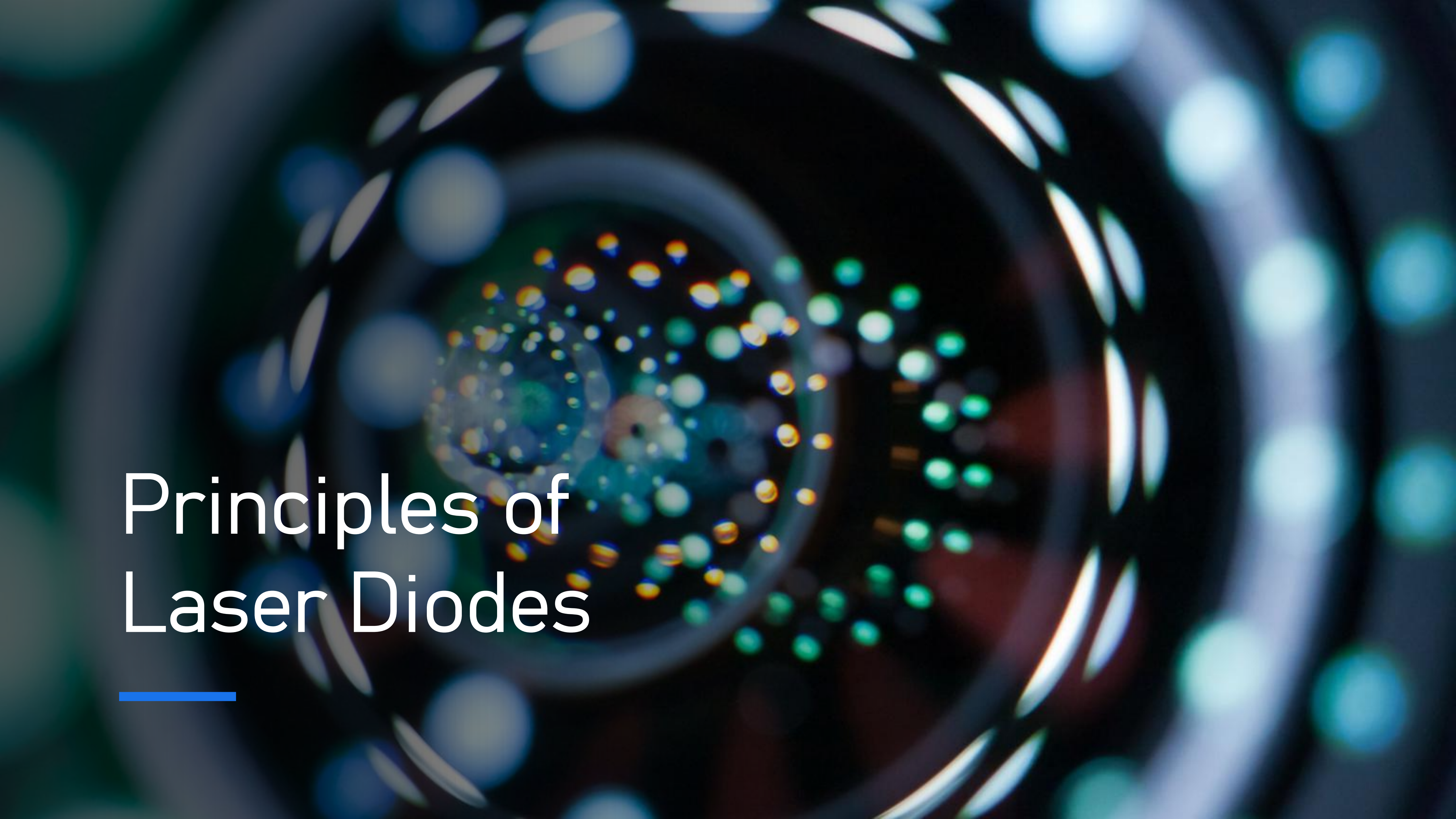
- Taking the condition for normal incidence, then the percent of the optical power that is generated internally in the device that is emitted into an air medium is

$$\eta_{ext} = \frac{1}{n(n+1)^2}$$

$$= \frac{1}{3.5(3.5+1)^2}$$

$$= 1.41\%$$

- This shows that only a small fraction of the internally generated optical power is emitted from the device.



Principles of Laser Diodes

Principles of Laser Diodes

- Lasers come in many forms, with mediums like gas, liquid, insulating crystals (solid-state), or semiconductors.
- Their sizes can range from a grain of salt to an entire room.
- The fundamental operating principle is the same for all types.
- The laser sources used almost exclusively in optical fiber systems are ***semiconductor laser diodes***.
  - They produce radiation with spatial and temporal coherence.
  - This means the output light is highly monochromatic (a single, pure color).
  - The light beam is also very directional.

Principles of Laser Diodes

- Laser action is the result of three core processes involving electron energy states:
  - Photon Absorption
  - Spontaneous Emission
  - Stimulated Emission

Principles of Laser Diodes

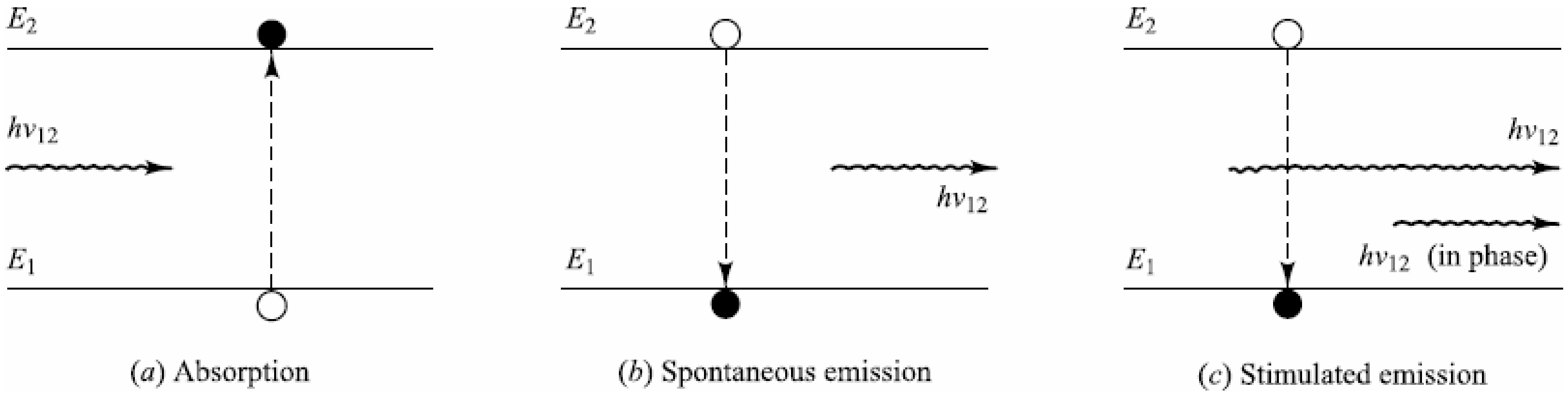


Fig. 4.16 The three key transition processes involved in laser action with the open circle representing the initial state of the electron and the heavy dot representing the final state; incident photons are shown on the left of each diagram and emitted photons are shown on the right

Photon Absorption

- This process uses two energy levels: a ground state (E_1) and an excited state (E_2).
- A transition between them involves a photon of energy $h\nu_{12} = E_2 - E_1$.
- An electron in the ground state (E_1) absorbs an incoming photon.
- This absorption gives the electron the energy to jump to the excited state (E_2).

Spontaneous Emission

- The excited state (E_2) is unstable.
- An electron in E_2 will shortly return to the ground state (E_1) on its own.
- When it drops, it releases a photon of energy $h\nu_{12}$.
- This process is called *Spontaneous Emission*.
- This emission is isotropic (occurs in all directions) and has a random phase.

Stimulated Emission

- This happens if an external photon (hv_{12}) impinges on the system while an electron is still in the excited state (E_2).
- The incoming photon stimulates the excited electron to immediately drop back to the ground state (E_1).
- This drop releases a new photon of energy hv_{12}.
- Crucially, this new photon is in phase with the incident photon.

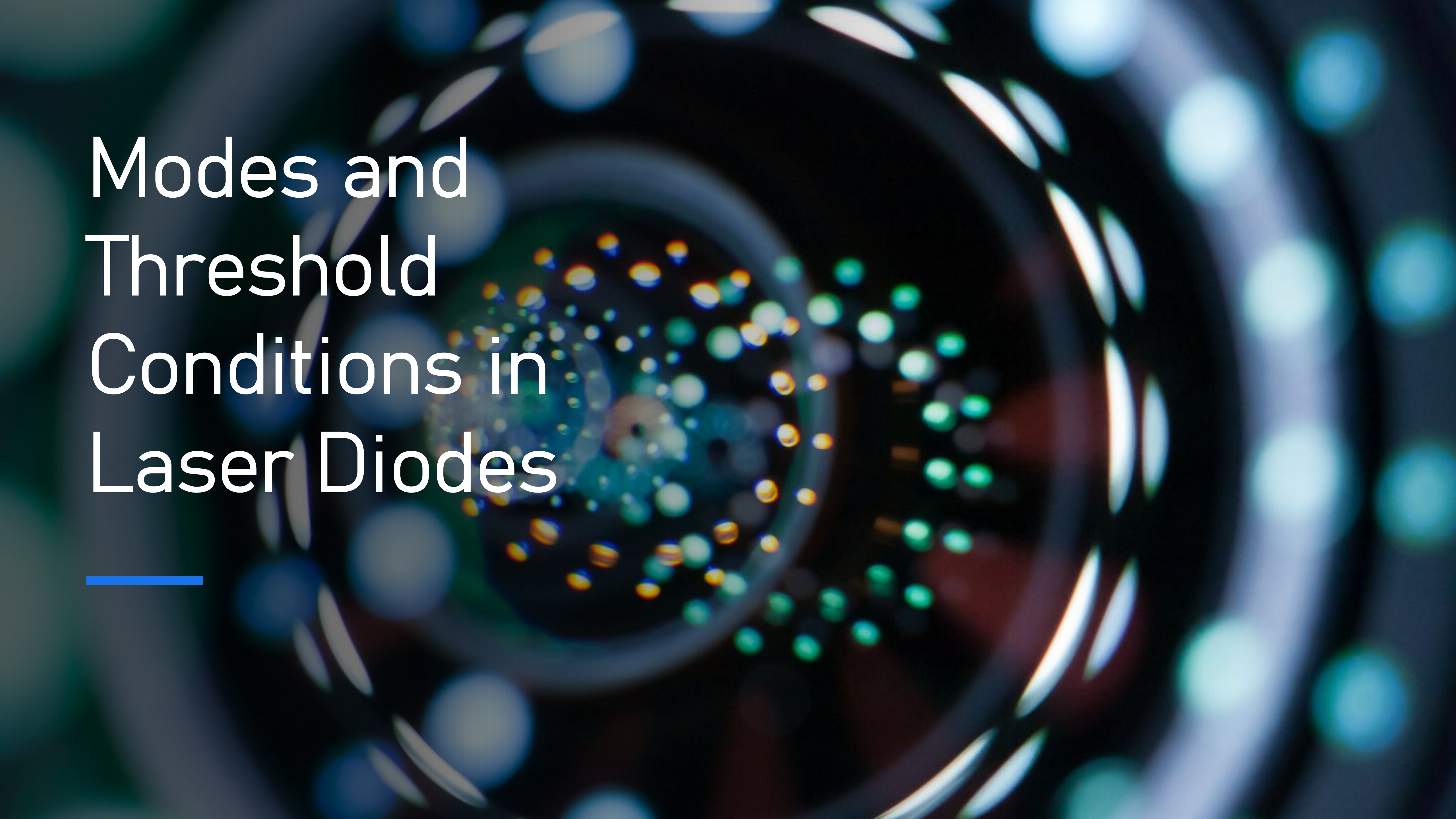
Population Inversion

- In a normal system (thermal equilibrium), most electrons are in the ground state (E_1), so absorption is the dominant process.
- To make stimulated emission dominate, more electrons must be in the excited state (E_2) than in the ground state (E_1).
- This non-equilibrium condition is known as **population inversion**.

Pumping

- Population inversion is not a natural state and must be achieved by an external process.
- This process is known as **"pumping"**.
- In semiconductor lasers, pumping is done by:
  - Injecting electrons into the material at the device contacts.
  - Using optical absorption (pumping the material with external photons).

Modes and Threshold Conditions in Laser Diodes



Laser Diodes in Optical Communications

- The semiconductor injection laser diode is preferred over the LED for bandwidths greater than ~200 MHz.
- Key Advantages:
  - Response times less than 1 ns.
  - Narrow spectral widths (1 nm or less).
  - High coupling power (tens of milliwatts) into small-core optical fibers.

Laser Diode vs. LED Construction

- Most laser diodes are multilayered heterojunction devices, which provide carrier and optical confinement.
- LEDs evolved from this design but are simpler to construct.
- LEDs have smaller temperature dependence and no catastrophic degradation.
- Laser diodes are more complicated, mainly due to the need for current confinement in a small lasing cavity.

The Fabry-Perot Resonator

- Semiconductor laser emission comes from transitions between energy bands, unlike the discrete levels in gas or solid-state lasers.
- Radiation is generated within a **Fabry-Perot resonator cavity**.
- This cavity is enclosed by two flat, partially reflecting mirrors directed toward each other.

The Fabry-Perot Resonator

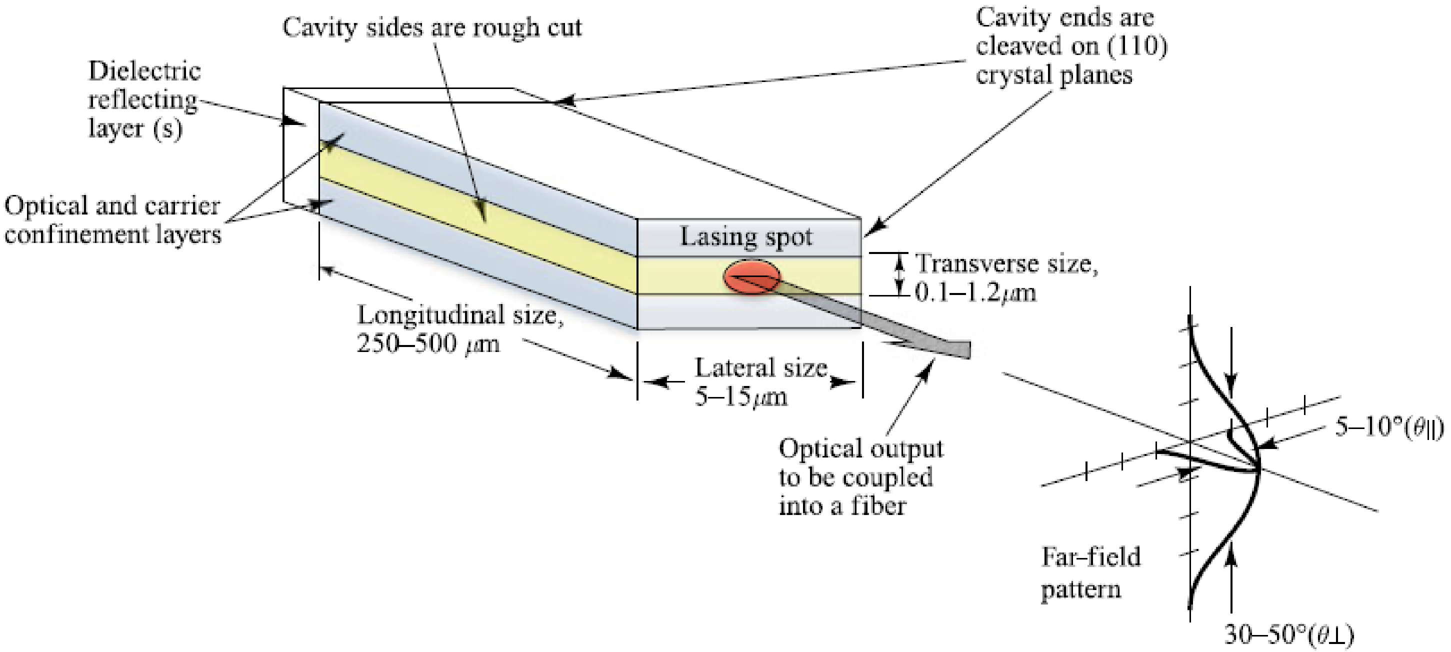


Fig. 4.17 Fabry-Perot resonator cavity for a laser diode where the cleaved crystal ends function as partially reflecting mirrors (note that the light beam emerging from the laser forms a vertical ellipse, even though the lasing spot at the active-area facet is a horizontal ellipse)

The Fabry-Perot Resonator

- Typical cavity dimensions:
  - Longitudinal: 250–500 μm (length)
  - Lateral: 5–15 μm (width)
  - Transverse: 0.1–0.2 μm (thickness)
- The light emerges as a vertical ellipse.
- Beam half-power width:
  - Lateral ($\boldsymbol{\theta}_{\parallel}$): $\approx 5\text{–}10°$
  - Transverse ($\boldsymbol{\theta}_{\perp}$): $\approx 30\text{–}50°$

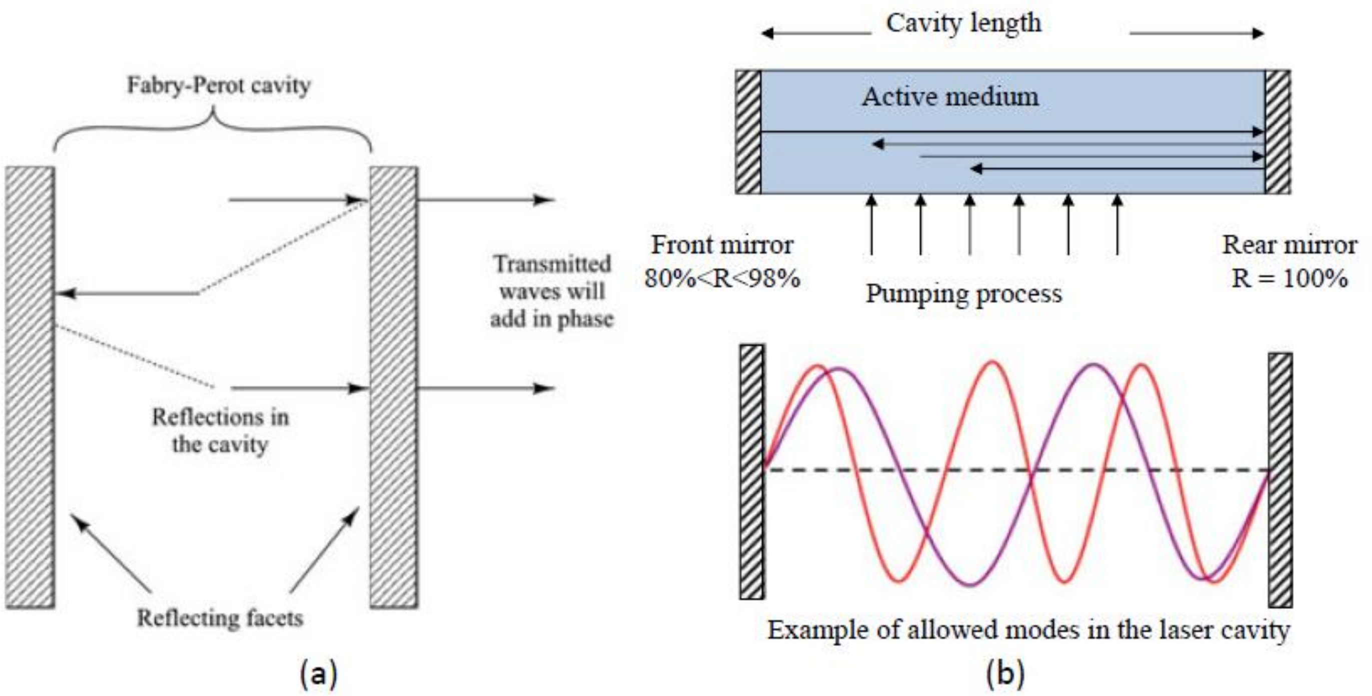


Fig. 4.18 **a** Two parallel light-reflecting mirrored surfaces define a Fabry-Perot resonator cavity; **b** schematic of a simple laser design and some allowed lasing modes

The Fabry-Perot Resonator

- The mirrors are made by cleaving the semiconductor crystal along natural planes.
- Their purpose is to establish strong optical feedback in the longitudinal direction.
- This feedback converts the device into an oscillator, with gain compensating for optical losses at specific resonant frequencies.
- The sides of the cavity are roughed to reduce unwanted lateral emissions.

The Fabry-Perot Resonator

- As light reflects back and forth, the electric fields interfere.
- Wavelengths that are integer multiples of the cavity length interfere **constructively**, and their amplitudes add.
- All other wavelengths interfere **destructively** and cancel out.
- The optical frequencies that interfere constructively are the **resonant frequencies**.
- These are called the **longitudinal modes** of the cavity.

The Fabry-Perot Resonator

- Spontaneously emitted photons at these resonant frequencies are reinforced and become very strong.
- The sharpness of these resonances depends on the mirror reflectivity (R).
- As reflectivity increases, the resonances become sharper.
- The Free Spectral Range (FSR) is the spacing between two successive resonant peaks.
- If *D* is the distance between the reflecting mirrors in a device of refractive index *n*, then at a peak wavelength λ the FSR is given by the expression

$$FSR = \frac{\lambda^2}{2nD}$$

The Fabry-Perot Resonator

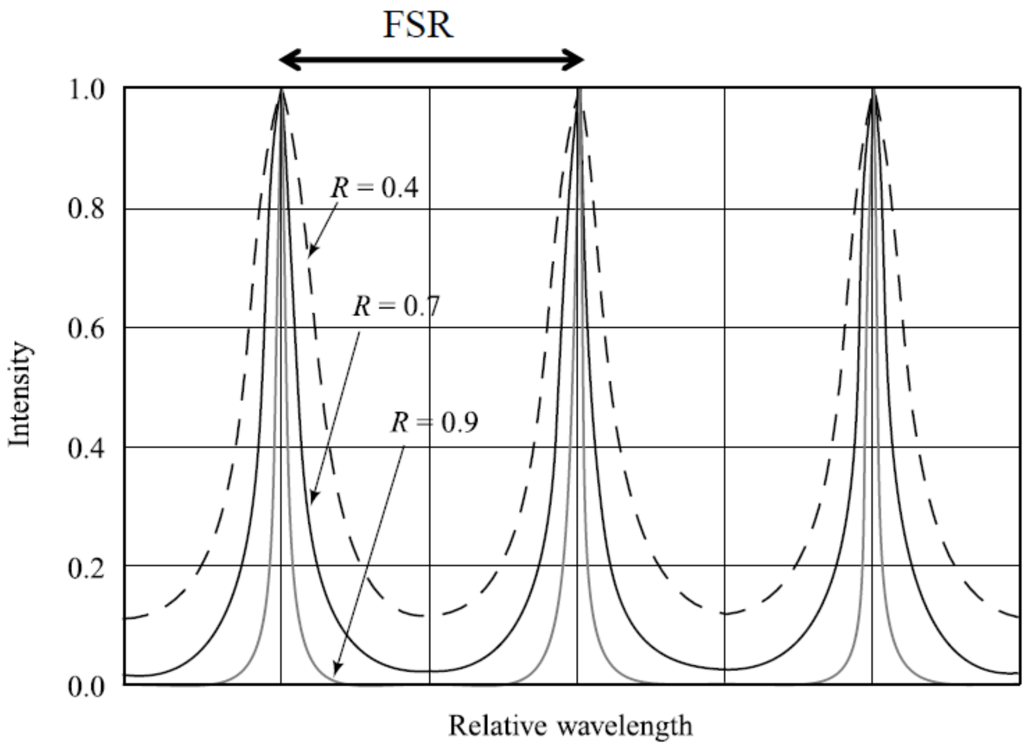


Fig. 4.19 Behavior of the resonant wavelengths in a Fabry-Perot cavity for three values of the mirror reflectivity showing that the distance between adjacent peaks is the free spectral range (FSR)

What is the FSR at an 850-nm wavelength for a 0.8-mm long GaAs Fabry-Perot cavity in which the refractive index is 3.5?

Solution:

Given $\lambda = 850\ nm$, $D = 0.8\ mm$, $n = 3.5$

The free spectral range (FSR) is given by

$$FSR = \frac{\lambda^2}{2nD}$$

$$= \frac{(0.85 \times 10^{-6})^2}{2(3.5)(0.80 \times 10^{-3})}$$

$$= 0.129\ \text{nm}$$

Distributed-Feedback (DFB) Lasers

- An alternative laser diode type is the Distributed-Feedback (DFB) laser.
- DFB lasers do not require cleaved facets (mirrors) for optical feedback.
- Instead, lasing action is obtained from **Bragg reflectors** (gratings) or periodic variations of the refractive index built into the structure.

Distributed-Feedback (DFB) Lasers

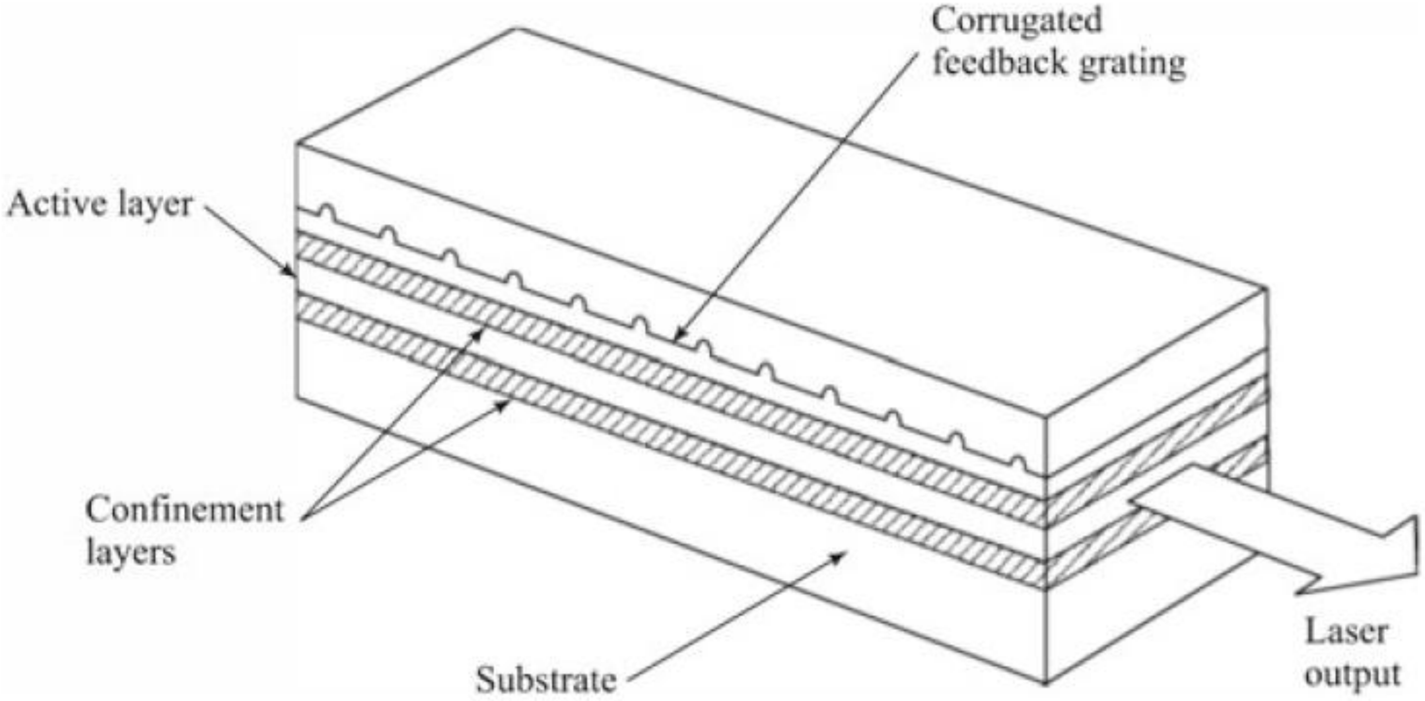


Fig. 4.20 Structure of a distributed-feedback (DFB) laser diode

Modes of the Cavity

- The optical radiation sets up patterns of electric and magnetic field lines called ***modes*** (TE and TM).
- Longitudinal modes: Related to the cavity length (L). They determine the frequency spectrum of the output.
- Lateral modes: Lie in the plane of the p-n junction. They depend on the cavity width and determine the lateral beam profile.
- Transverse modes: Perpendicular to the p-n junction. They determine the radiation pattern and threshold current density.

The Lasing Condition

- Lasing is the condition where light amplification becomes possible.
- The intensity of radiation (I) at a photon energy hv as it travels a distance z is:

$$I(z) = I(0)\exp\{[\Gamma g(h\nu) - \alpha_{mat}(h\nu)]z\}$$

where:

$g(hv)$ is the gain coefficient

α_{mat} is the effective absorption coefficient (loss)

Γ is the optical-field confinement factor (fraction of power in the active layer)

The Threshold Condition

- Lasing occurs when the gain of a guided mode is sufficient to exceed the optical loss during one round trip ($z = 2L$).
- A steady-state oscillation is reached at the threshold.
- The amplitude condition for this is $I(2L) = I(0)$.
- This means the optical gain must equal the total loss (α_t)in the cavity.
- Gain g must be $\geq g_{th}$ for lasing to occur.

Threshold Gain Equation

- The threshold gain (g_{th}) is the point where gain equals all losses.
- The total loss (α_t) is the sum of material absorption and end mirror losses.

$$g_{th} = \alpha_t = \alpha_{mat} + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right) = \alpha_{mat} + \alpha_{end}$$

where α_{end} is the end mirror loss in the lasing cavity.

R_1 and R_2 are the reflectivities of the two mirrors.

Output Power vs. Drive Current

- At low drive currents, only broad spontaneous emission (like an LED) occurs.
- At the lasing threshold (I_{th}), a sharp, dramatic increase in optical power occurs.
- As the current passes the threshold, the spectral range and beam width both narrow significantly.
- The threshold current (I_{th}) is found by extrapolating the linear lasing region of the power-current curve.

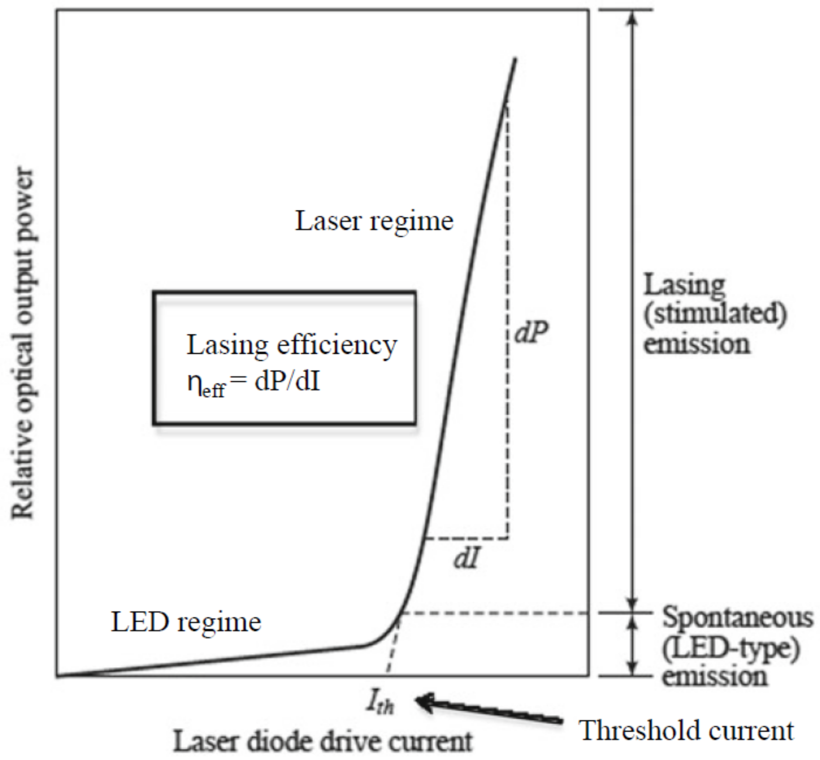


Fig. 4.21 Relationship between optical output power and laser diode drive current

Threshold Current Density

- For lasers with strong carrier confinement, the threshold current density (J_{th}) is related to the threshold gain (g_{th}):

$$g_{th} = \beta_{th} J_{th}$$

β_{th} is a gain factor constant that depends on the specific device construction.

Laser Diode Rate Equations

Laser Diode Rate Equations

- These equations determine the relationship between the optical output power and the diode drive current.
- They govern the interaction of photons (Φ) and electrons (n) in the active laser region.
- The carrier population is balanced by three main processes:
  - Carrier Injection
  - Spontaneous Recombination
  - Stimulated Emission

The Photon Rate Equation

- This equation governs the change in the number of photons (Φ).

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}}$$

$$= stimulated\ emission + spontaneous\ emission + photon\ loss$$

$Cn\Phi$ is the source of photons from stimulated emission.

R_{sp} is the spontaneous emission into the lasing mode (a small value).

$\frac{\Phi}{\tau_{ph}}$ is the decay of photons due to losses in the cavity.

The Electron Rate Equation

- This equation governs the change in the number of electrons ($\boldsymbol{n}$).

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi$$

$$= injection + spontaneous\ recombination + stimulated\ emission$$

$\frac{J}{qd}$ is the increase in electrons from the injection current.

$\frac{n}{\tau_{ph}}$ is the loss of electrons from spontaneous recombination.

$Cn\Phi$ is the loss of electrons due to stimulated emission.

Key Equation Variables

C: Coefficient for the strength of optical interactions.

R_{sp} : Rate of spontaneous emission into the lasing mode.

τ_{ph}: Photon lifetime.

τ_{sp} : Spontaneous recombination lifetime.

J: Injection-current density.

q: Electron charge.

d: Depth of the carrier-confinement region.

The Threshold Condition

- To find the output power, we solve for a steady-state condition, where the rate of change is zero $\left(\frac{d\Phi}{dt} = 0 \; and \; \frac{dn}{dt} = 0\right)$.
- From the photon equation, for the number of photons (Φ) to increase, the gain from stimulated emission must be greater than or equal to the loss.

$$Cn - \frac{1}{\tau_{ph}} \geq 0$$

- This shows that the electron concentration (n) must exceed a threshold value (n_{th}) for lasing to begin.

Threshold Current

- The threshold current (J_{th}) is the current required to maintain the threshold electron density (n_{th}) when $\Phi = 0$ (at the brink of lasing).
- From the electron rate equation in the steady state ($J = J_{th}, n = n_{th}, \Phi = 0$):

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}}$$

- This defines the threshold current density needed to sustain the electron population against spontaneous recombination:

$$\frac{J_{th}}{qd} = \frac{n_{th}}{\tau_{sp}}$$

Steady-State Photon Density ($\boldsymbol{\Phi_s}$)

- We solve both steady-state equations at the lasing threshold ($n = n_{th}$).
- By adding the two rate equations (photon and electron) and substituting the expression for J_{th}, we can solve for the steady-state photon density, Φ_s.
- The resulting number of photons per unit volume is:

$$\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp}$$

- The first term represents photons from stimulated emission.
  - This power is highly concentrated in one or a few modes.
- The second term represents photons from spontaneous emission.
  - This power is spread across all possible modes (e.g., ~10^8 modes).

External Differential Quantum Efficiency

External Differential Quantum Efficiency

- External Differential Quantum Efficiency (η_{ext}) is defined as the number of photons emitted per radiative electron-hole pair recombination above the threshold.
- This assumes that above the threshold, the gain coefficient remains fixed at g_{th}.
- The efficiency is given by the formula:

$$\eta_{ext} = \eta_i \frac{(g_{th} - \alpha_{mat})}{g_{th}}$$

η_i is the internal quantum efficiency.

η_i is not a well-defined quantity in laser diodes, but measurements typically show it is 0.6 – 0.7 at room temperature.

External Differential Quantum Efficiency

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

$$\eta_{ext} = \frac{q}{E_g}\frac{dP}{dI}$$

E_g is the bandgap energy in electron volts (eV).

- A more practical version of the experimental formula, using wavelength, is:

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

λ is the emission wavelength in micrometers.

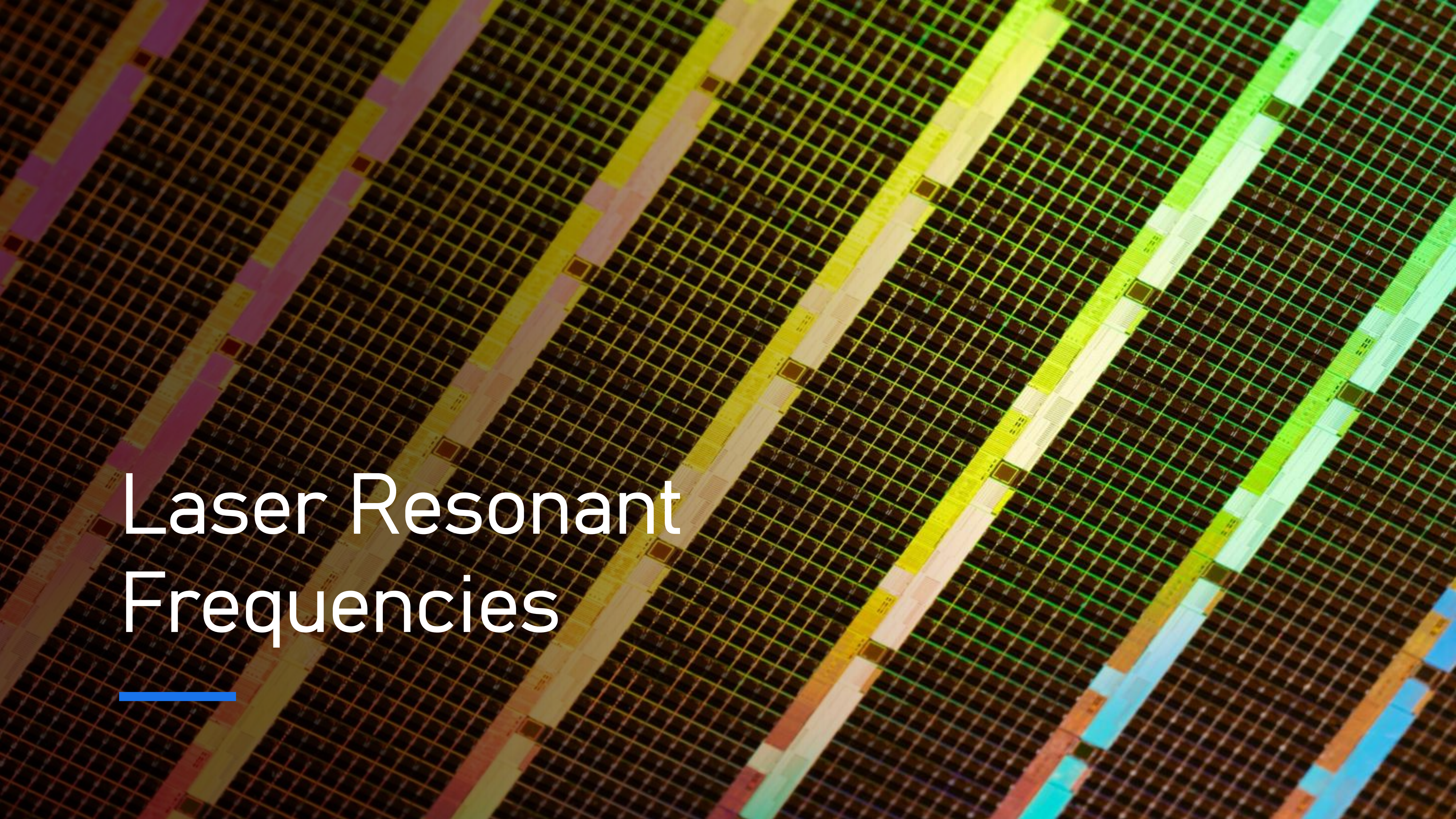
dP is the incremental change in optical power (in mW).

dI is the incremental change in drive current (in mA).

External Differential Quantum Efficiency

- For standard semiconductor lasers, external differential quantum efficiencies of 15—20% per facet are typical.
- High-quality devices have differential quantum efficiencies of 30—40%.

Laser Resonant Frequencies



Laser Resonant Frequencies

- The resonant frequencies of the laser are determined by the phase condition for a steady-state oscillation.

$$e^{-j2\beta L} = 1$$

- This holds true when the round-trip phase shift is an integer multiple of 2π.

$$2\beta L = 2\pi m$$

m is an integer.

β is the propagation constant.

L is the cavity length.

Laser Resonant Frequencies

- Using the propagation constant $\beta = 2\pi n/\lambda$, the condition becomes $\boldsymbol{m} = \frac{L}{\lambda/2n}$
- This means the cavity resonates (a standing-wave pattern exists) when an integer number $(\boldsymbol{m})$ of half-wavelengths $(\lambda/2n)$ spans the region between the mirrors.
- This can also be expressed in terms of frequency $(\boldsymbol{\nu})$:

$$m = \left(\frac{2Ln}{c}\right)\nu$$

Laser Modes and Gain

- The laser's gain is a function of frequency (or wavelength).
- The frequencies that satisfy the resonance condition are the **modes** of the laser.
- Lasers can be **single-mode** or **multimode**, depending on how many frequencies satisfy the gain and resonance conditions.
- The gain-versus-wavelength relationship can be assumed to have a Gaussian form:

$$g(\lambda) = g(0)\exp\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]$$

where λ_0 is the wavelength at the center of the spectrum, σ is the spectral width of the gain, and the maximum gain $g(0)$ is proportional to the population inversion.

Frequency Spacing of Longitudinal Modes

- We can find the frequency spacing ($\Delta\nu$) between two successive longitudinal modes (m and $m-1$).

- From $m = \left(\frac{2Ln}{c}\right)\nu_m$ and $m-1 = \left(\frac{2Ln}{c}\right)\nu_{m-1}$, Subtracting the two equations gives:

$$1 = \left(\frac{2Ln}{c}\right)(\nu_m - \nu_{m-1}) = \left(\frac{2Ln}{c}\right)\Delta\nu$$

- The frequency spacing is:

$$\Delta\nu = \frac{c}{2Ln}$$

Wavelength Spacing of Longitudinal Modes

- The frequency spacing can be related to the wavelength spacing ($\Delta\lambda$) using the relationship

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda}$$

- This gives the wavelength spacing between modes as:

$$\Delta\lambda = \frac{\lambda^2}{2Ln}$$

Multimode Laser Output Spectrum

- The output spectrum of a multimode laser is a combination of the gain curve and the allowed resonant modes.
- The output consists of a series of sharp peaks (the modes).
- The spacing of these peaks is determined by $\Delta\lambda$.
- The overall shape (envelope) of the peaks is determined by the Gaussian gain curve $g(\lambda)$.

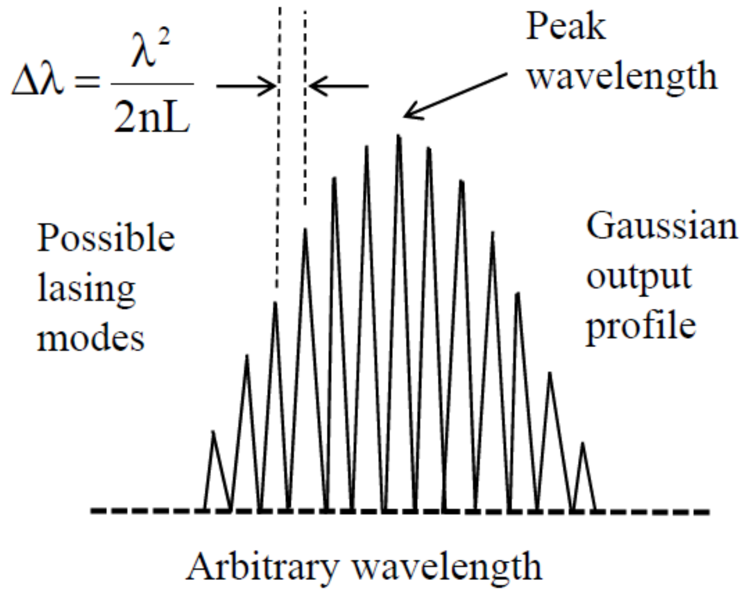


Fig. 4.22 Typical spectrum from a Fabry-Perot GaAlAs/GaAs laser diode

Photodetectors

Photodetectors

- A photodetector is the first component in an optical receiver.
- Its primary function is to sense the incoming optical signal (which is often weakened and distorted).
- It converts the variation of this optical power into a correspondingly varying electric current.
- Semiconductor-based photodiodes are used almost exclusively for fiber optic systems.
- **Key Advantages:**
  - Small size
  - Suitable materials for operational wavelengths
  - High sensitivity
  - Fast response time
- The two main types are the **pin photodiode** and the **avalanche photodiode (APD)**.

The pin Photodetector

The pin Photodetector

- The device structure consists of **p**-type and **n**-type semiconductor regions.
- These regions are separated by a very lightly n-doped **intrinsic (i) region**.
- This structure gives the device its name: p-i-n.
- In normal operation, a large **reverse-bias voltage** is applied across the device.
- This voltage causes the intrinsic (i) region to become **fully depleted** of mobile charge carriers (electrons and holes).
- This depletion creates a wide region with a high electric field.

The pin Photodetector

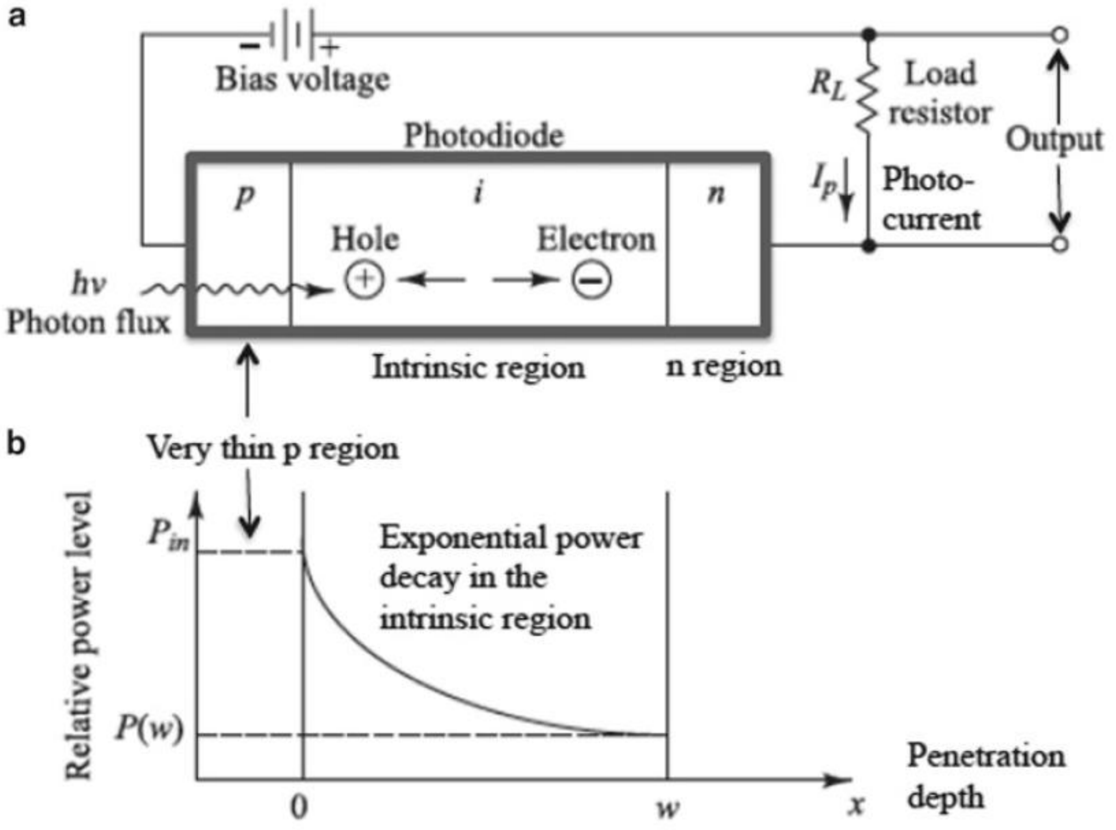


Fig. 6.1 **a** Representation of a *pin* photodiode circuit with an applied reverse bias. **b** An incident optical power level decays exponentially inside the device

The pin Photodetector

- An incident photon with energy greater than or equal to the bandgap energy (E_g) of the material is absorbed.
- This absorption gives an electron enough energy to jump from the valence band to the conduction band.
  - This process creates a mobile electron-hole pair. These are known as ***photocarriers***.

The pin Photodetector

- These photocarriers are generated mainly in the depleted intrinsic region.
- The high electric field in this region sweeps the carriers apart (electrons to the n-side, holes to the p-side).
- The carriers are collected across the reverse-biased junction, creating a current in the external circuit.
- This current is known as the **photocurrent**.
- The p region is made very thin so that most photons are absorbed in the wide i region, not on the surface.

The pin Photodetector

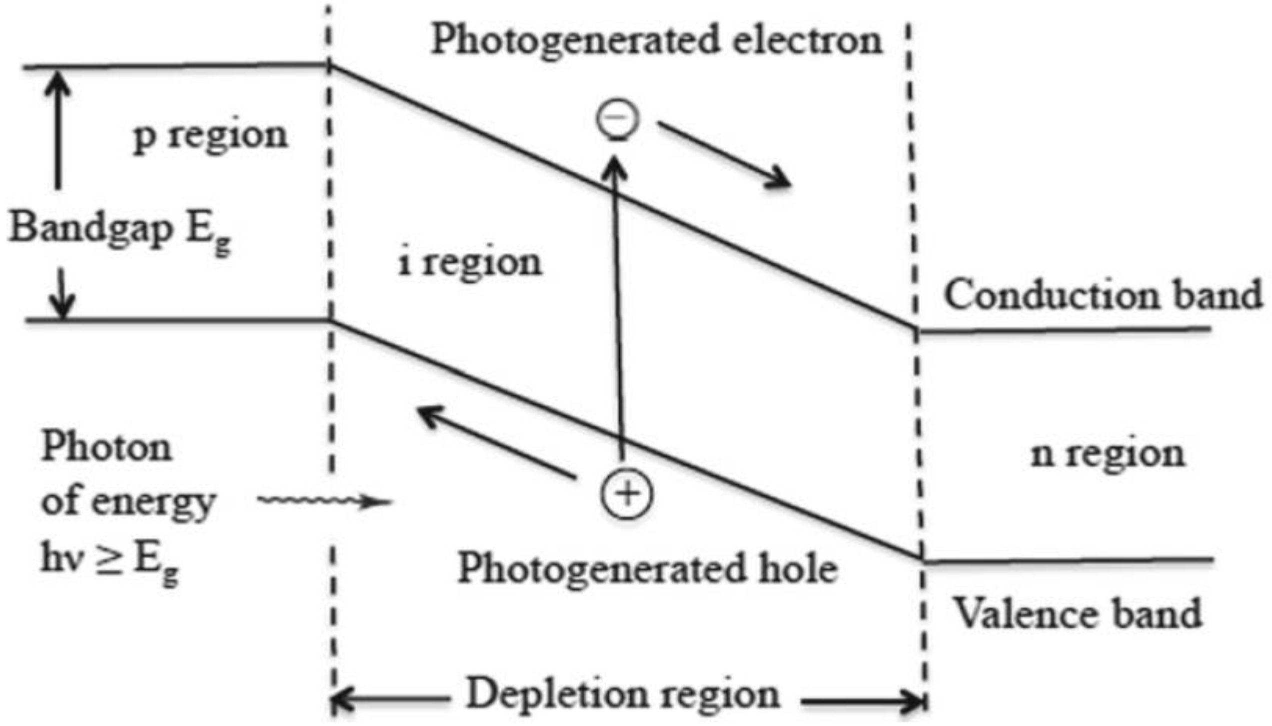


Fig. 6.2 Simple energy-band diagram for a *pin* photodiode showing that photons with energies greater than or equal to the bandgap energy E_g can generate free electron–hole pairs that act as photocurrent carriers

Quantum Efficiency ($\boldsymbol{\eta}$)

- A key parameter for a photodetector.
- It is the number of electron-hole pairs generated divided by the number of absorbed incident photons.

$$\eta = \frac{\text{number of electron-hole pairs generated}}{\text{number of absorbed incident photons}} = \frac{i_p/q}{P_{in}/h\nu}$$

- Here, i_p is the photocurrent generated by an optical power P_{in} incident on the photodetector.

Responsivity ($\Re$)

- A very useful practical performance measure.
- It is the photocurrent generated per unit of incident optical power.

$$\mathscr{R} = \frac{i_p}{P_{in}} = \frac{\eta q}{h\nu}$$

- The unit for responsivity is Amps per Watt (A/W).
- Most photodiodes are linear, meaning $\Re$ is constant for a given wavelength.

The Efficiency vs. Speed Trade-off

- A fundamental design compromise must be made.
- **High Quantum Efficiency:** Requires a **thick** depletion layer to absorb a large fraction of incident light.
- **Fast Response Speed:** Requires a **thin** depletion layer so carriers can drift across the junction quickly.
- A thick layer increases absorption but slows the device; a thin layer is fast but misses photons.

Avalanche Photodiodes

Avalanche Photodiodes

- Avalanche Photodiodes (APDs) internally **multiply** the primary signal photocurrent.
- This multiplication happens *before* the signal enters the input circuitry of the following amplifier.
- This action increases receiver sensitivity because the photocurrent is multiplied before it encounters the thermal noise associated with the receiver circuit.

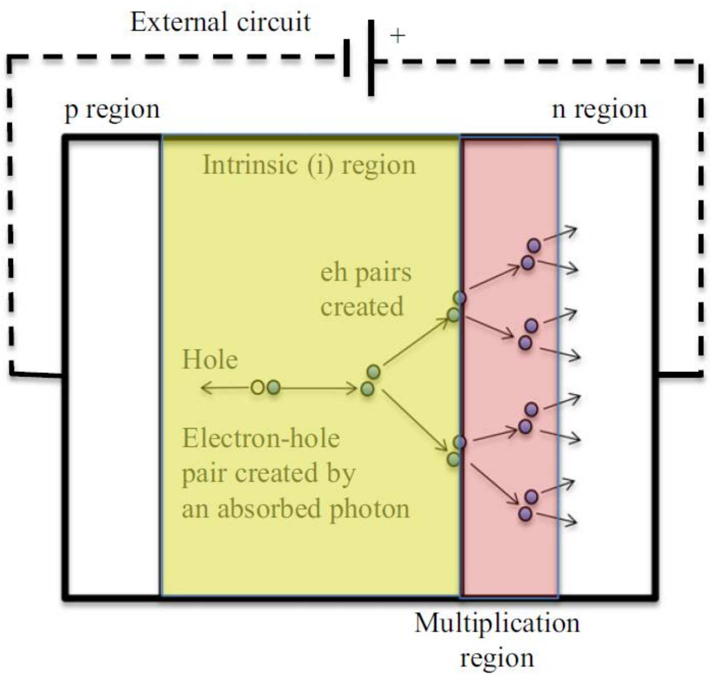


Fig. 6.5 Concept of photocurrent multiplication through an avalanche effect in an APD

Avalanche Photodiodes

- Multiplication takes place when photon-generated carriers traverse a **multiplication region**.
- This region contains a **very high electric field**.
- In this high-field region, a carrier (electron or hole) can gain enough energy to ionize bound electrons in the valence band upon colliding with them.
- This process is known as **impact ionization**.

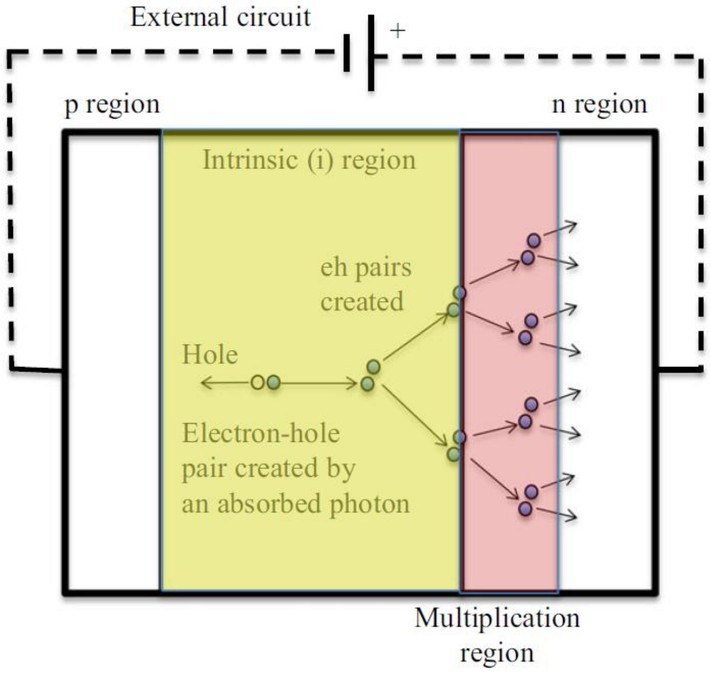


Fig. 6.5 Concept of photocurrent multiplication through an avalanche effect in an APD

Avalanche Photodiodes

- The newly created carriers from impact ionization are also accelerated by the high electric field.
- They, in turn, gain enough energy to cause **further** impact ionizations.
- This repeating phenomenon creates a "chain reaction" or cascade of carriers.
- This process is known as the **avalanche effect**.

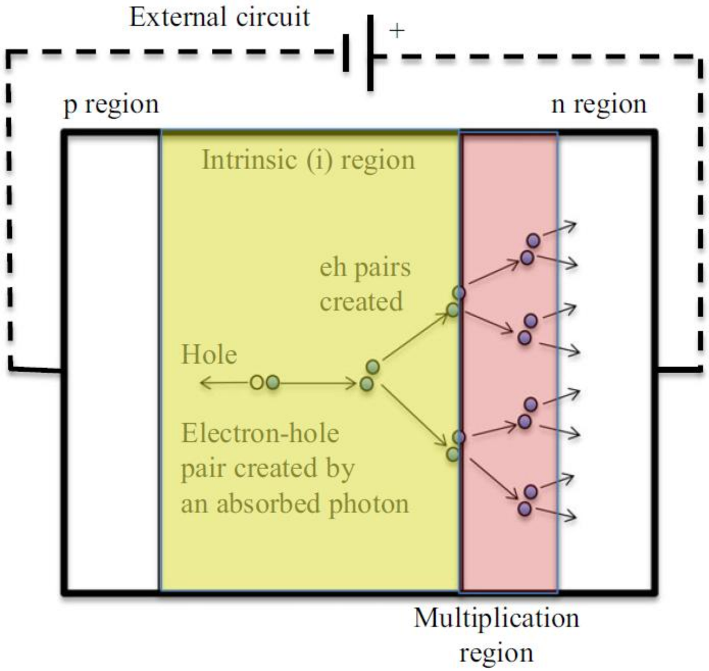


Fig. 6.5 Concept of photocurrent multiplication through an avalanche effect in an APD

The Multiplication Factor ($\boldsymbol{M}$)

- The multiplication (M) for all carriers generated in the photodiode is defined by:

$$M = \frac{i_M}{i_p}$$

i_M is the average value of the total multiplied output current.

i_p is the primary unmultiplied photocurrent.

The avalanche mechanism is a statistical process, so the measured value of M is an average quantity.

APD Responsivity ($\Re_{APD}$)

- The performance of an APD is characterized by its responsivity, $\Re_{APD}$.
- It is related to the responsivity of a pin diode ($\Re$), but includes the multiplication factor M.

$$\mathscr{R}_{\text{APD}} = \frac{\eta q}{h\nu} M = \mathscr{R} M$$

- $\Re$ is the unity gain responsivity (the responsivity the device would have without any multiplication).

Reference

- Gerd Keiser, ***Optical Fiber Communication***, 5th Edition, McGraw Hill Education (India) Private Limited, 2016. ISBN:1-25-900687-5.