Semiconductor Sources for Optical Communications

By

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Considerations with Optical Sources

- Physical dimensions to suit the fiber
- Narrow radiation pattern (beam width)
- Linearity (output light power proportional to driving current)

Considerations with Optical Sources

- Ability to be directly modulated by varying driving current
- Fast response time (wide band)
- Adequate output power into the fiber

Considerations…

- Narrow spectral width (or line width)
- Stability and efficiency
- Driving circuit issues
- Reliability and cost

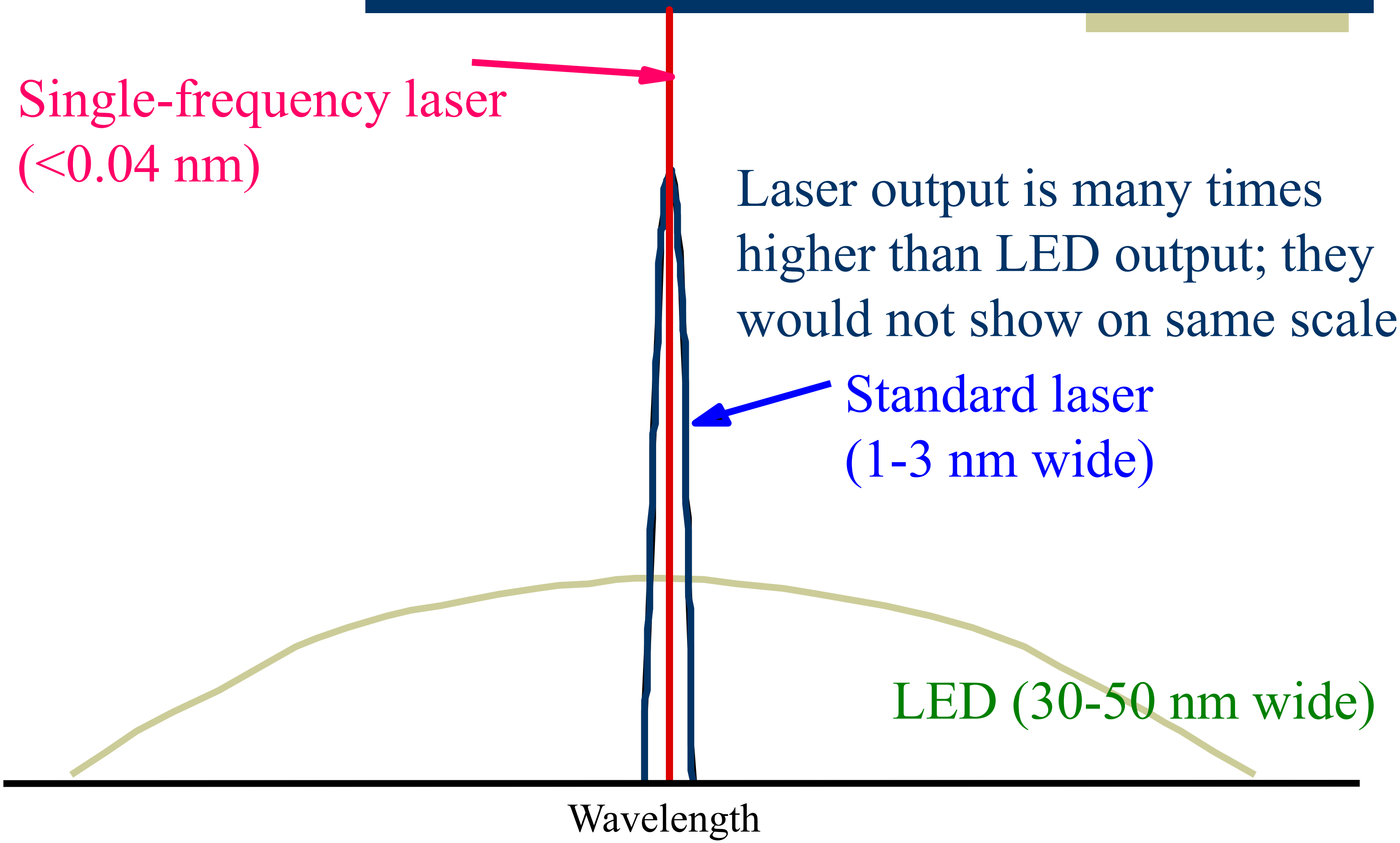
Semiconductor Light Sources

- LED
- Laser Diode

Semiconductor Light Sources

- A PN junction (that consists of direct band gap semiconductor materials) acts as the *active* or *recombination* region.
- When the PN junction is forward biased, electrons and holes recombine either *radiatively* (emitting photons) or *non-radiatively* (emitting heat). This is simple LED operation.
- In a LASER, the photon is further processed in a resonance cavity to achieve a *coherent, highly directional* optical beam with *narrow linewidth.*

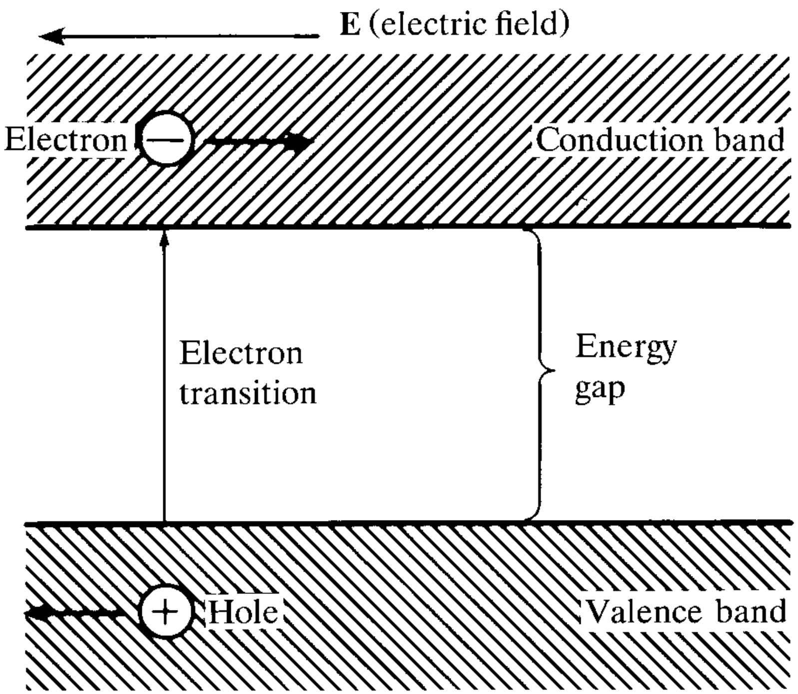
LED vs. laser spectral width



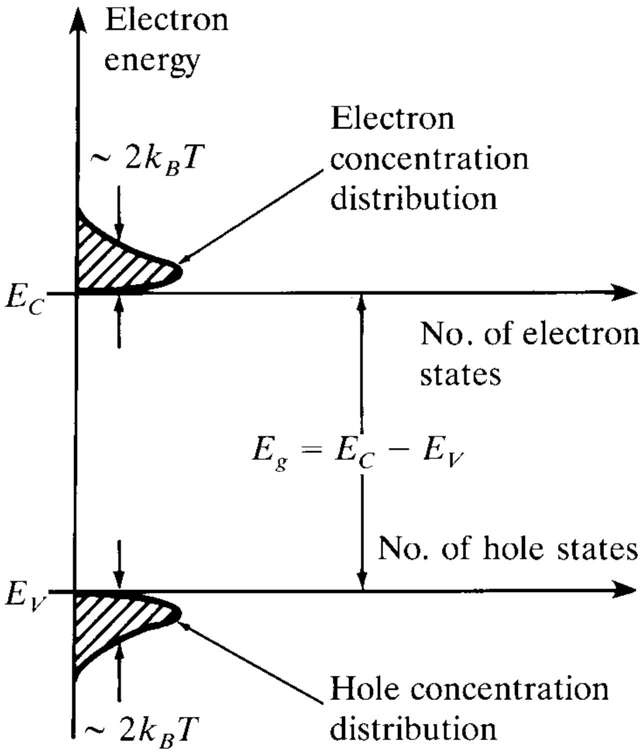
Light Emission

- Basic LED operation: When an electron jumps from a higher energy state (E_c) to a lower energy state (E_v) the difference in energy $E_c - E_v$ is released either
  - as a photon of energy $E = h\nu$ (radiative recombination)
  - as heat (non-radiative recombination)

Energy-Bands



(a)



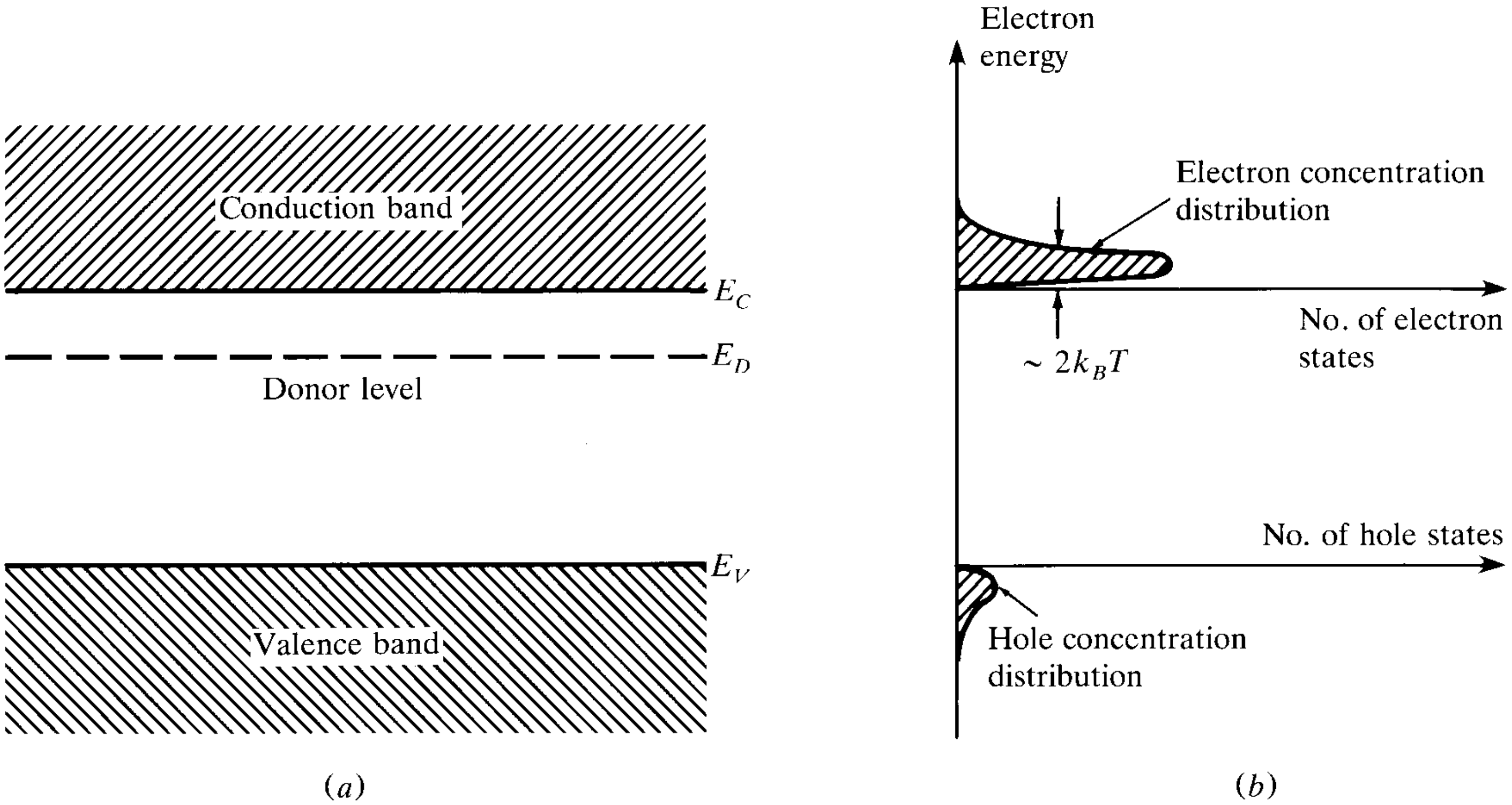
(b)

In a pure Gp. IV material, equal number of holes and electrons exist at different energy levels.

$$n = p = n_i = K \exp\left(-\frac{E_g}{2k_BT}\right)$$

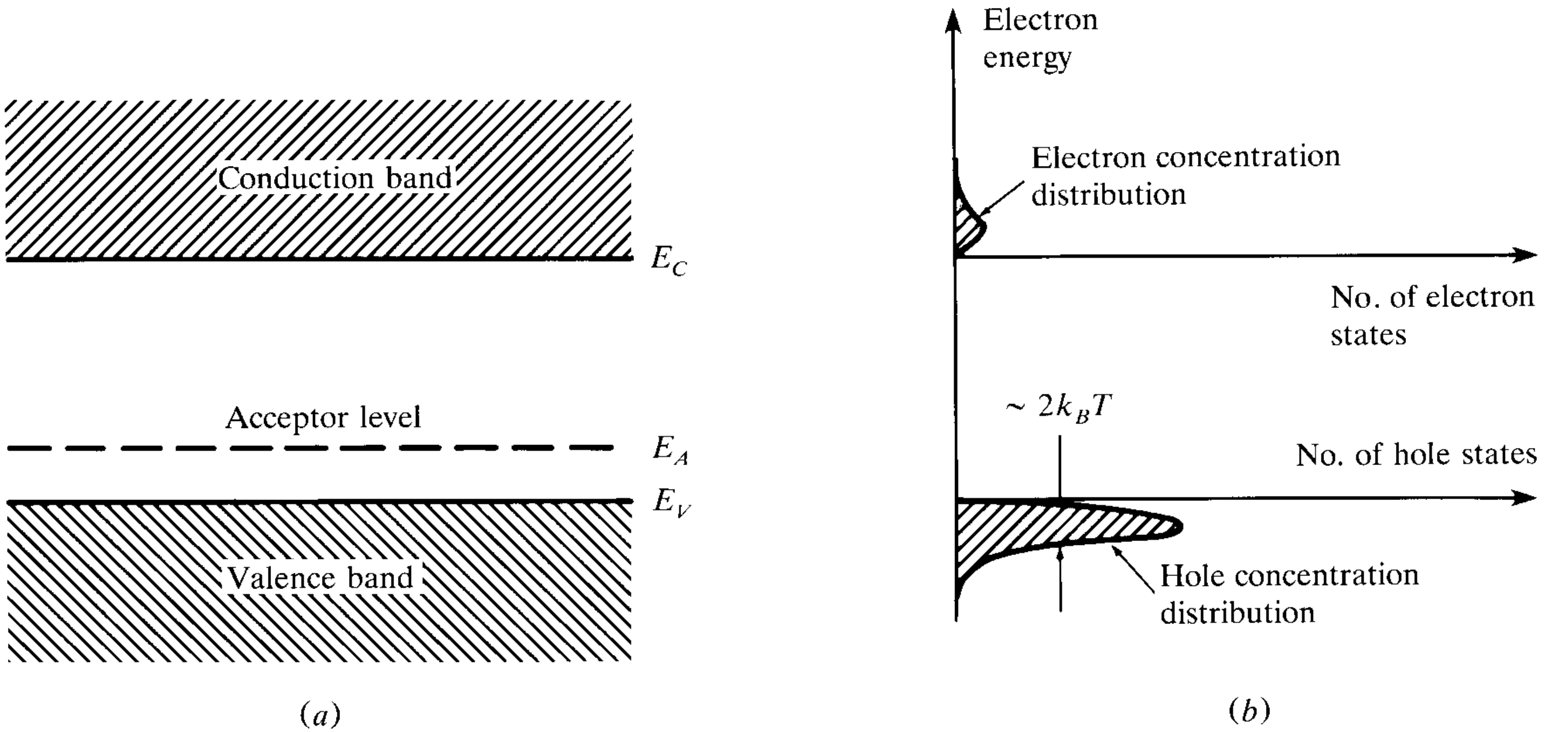
$$K = 2(2\pi k_B T/h^2)^{3/2}(m_e m_h)^{3/4}$$

n-type material



Adding group V impurity will create an n- type material

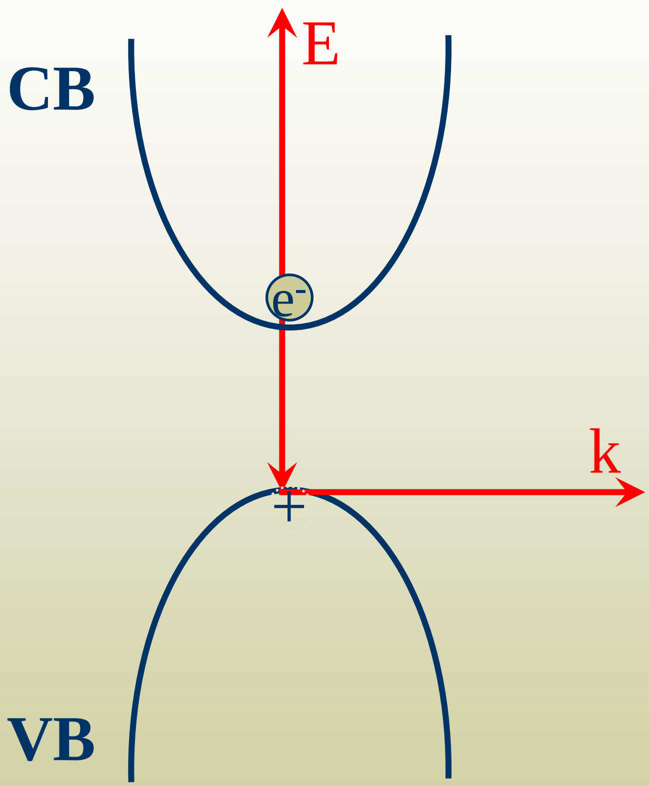
p-type material



Adding group III impurity will create a p-type material

Direct an indirect-band gap materials :

Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)

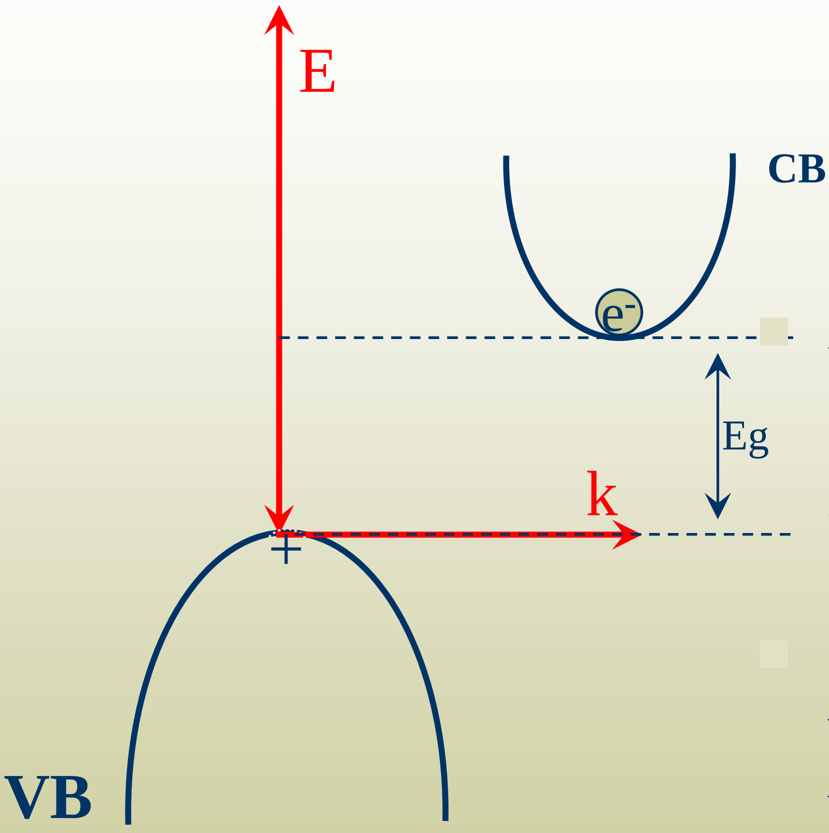


- For a *direct-band gap material*, the minimum of the conduction band and maximum of the valance band lies at the same momentum, k, values.

- When an electron sitting at the bottom of the CB recombines with a hole sitting at the top of the VB, there will be no change in momentum values.

- Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

Indirect-band gap s/c's (e.g. Si and Ge)



- For an indirect-band gap material; the minimum of the CB and maximum of the VB lie at different k-values.
- When an e^- and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.

Phonon

- Atoms vibrate about their mean position at a finite temperature.These vibrations produce vibrational waves inside the crystal.
- Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .
- Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.

The Light Emitting Diode (LED)

- For fiber-optics, the LED should have a high radiance (light intensity), fast response time and a high quantum efficiency
- Double or single hetero-structure devices
- Surface emitting (diffused radiation) Vs Edge emitting (more directional) LED's
- Emitted wavelength depends on bandgap energy

$$E_g = h\nu = hc/\lambda$$

Heterojunction

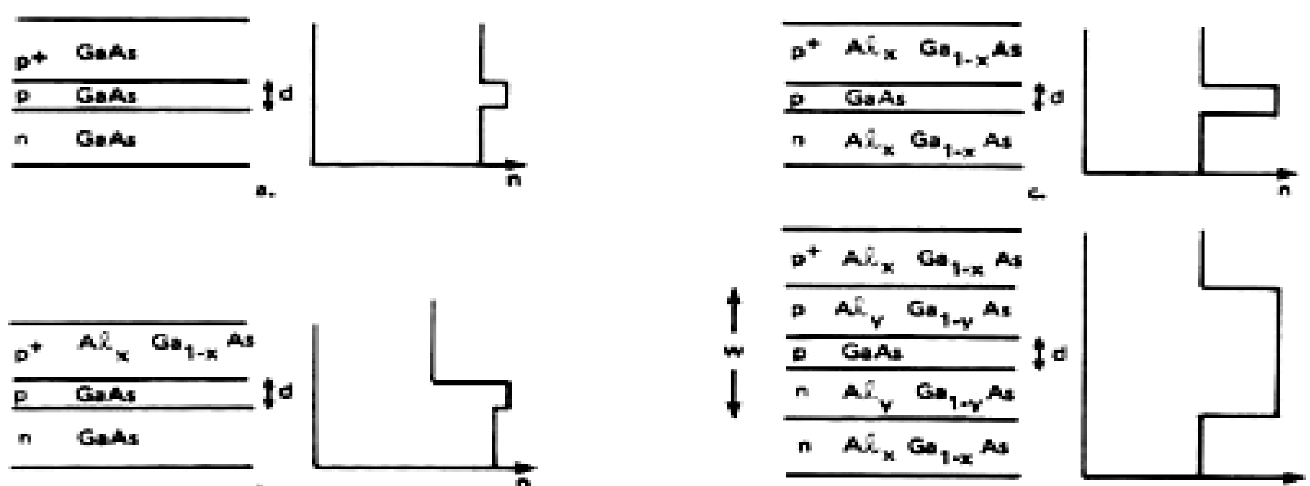
- Heterojunction is the advanced junction design to reduce diffraction loss in the optical cavity.
- This is accomplished by modification of the laser material to control the index of refraction of the cavity and the width of the junction.

- ***The p-n junction of the basic GaAs LED/laser described before is called a homojunction because only one type of semiconductor material is used in the junction with different dopants to produce the junction itself.***
- ***The index of refraction of the material depends upon the impurity used and the doping level.***

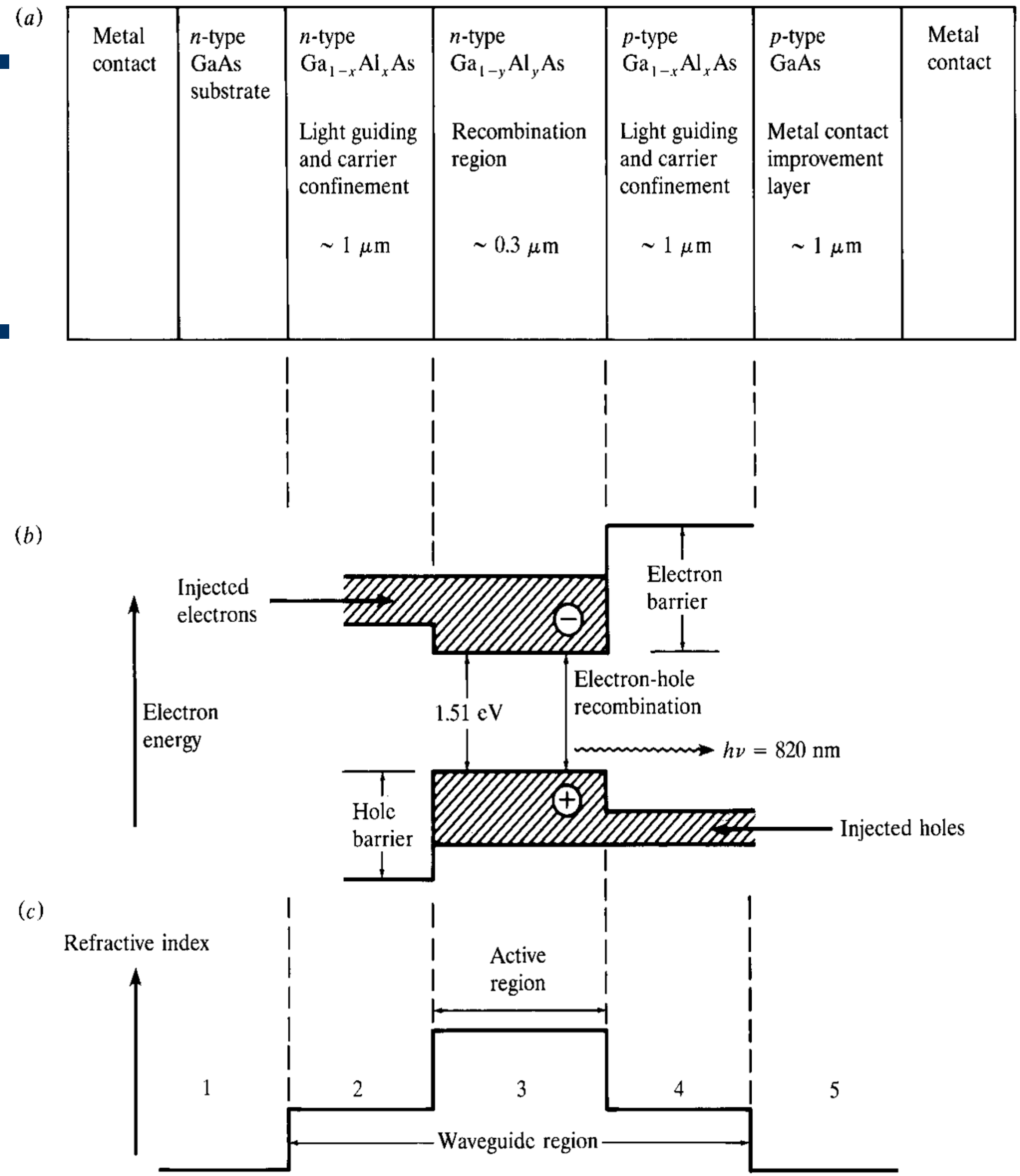
- ***The Heterojunction*** region is actually lightly doped with p-type material and has the highest index of refraction.
- The n-type material and the more heavily doped p-type material both have lower indices of refraction.
- This produces a light pipe effect that helps to confine the laser light to the active junction region. In the homojunction, however, this index difference is low and much light is lost.

Gallium Arsenide-Aluminum Gallium Arsenide Heterojunction

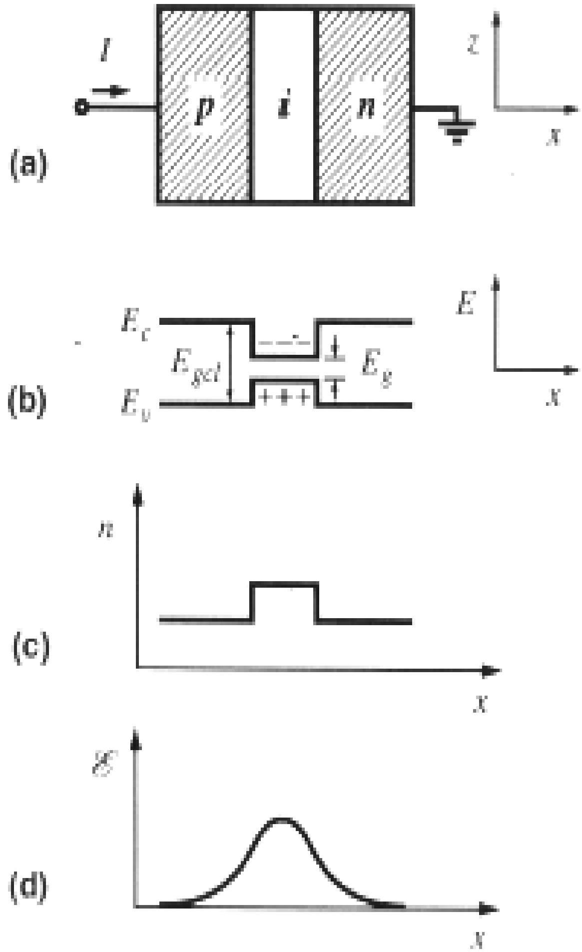
- **Structure and index of refraction n for various types of junctions in gallium arsenide with a junction width d.**
- **(*a*) is for a homojunction.**
- **(*b*) is for a gallium arsenide-aluminum gallium arsenide single heterojunction.**
- **(*c*) is for a gallium arsenide-aluminum gallium arsenide double heterojunction with improved optical confinement.**
- **(*d*) is for a double heterojunction with a large optical cavity of width w.**



Double-heterostructure configuration



Structure of a Generic Light Emitter: Double-Heterostructure Device



Double Heterostructure provides **transverse confinement** of both Carriers and Photons

(transverse direction → direction normal to the plane of the *pn* junction, x axis)

a) Schematic of a structure
b) Energy diagram of the conduction and valence bands vs. transverse distance
c) Refractive index profile
d) Electric field profile for a mode traveling in the z-direction

OPERATING WAVELENGTH

Fiber optic communication systems operate in the

- **850-nm,**
- **1300-nm, and**
- **1550-nm wavelength windows.**
- **Semiconductor sources are designed to operate at wavelengths that minimize optical fiber absorption and maximize system bandwidth**

LIGHT-EMITTING DIODES

- **A light-emitting diode (LED) is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it. Typically LEDs for the 850-nm region are fabricated using GaAs and AlGaAs. LEDs for the 1300-nm and 1550-nm regions are fabricated using InGaAsP and InP.**

LED Wavelength

$$\lambda(\mu m) = \frac{1.2399}{E(\mathrm{eV})}$$

λ = hc/E(eV)

λ = wavelength in microns
H = Planks constant
C = speed of light
E = Photon energy in eV

Band gap energy

$Ga_{1-x}Al_xAs.$

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

$In_{1-x}Ga_xAs_yP_{1-y}$

$$y \simeq 2.20x \text{ with } 0 \leq x \leq 0.47.$$

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

Bandgap Energy and Possible Wavelength Ranges in Various Materials

Material	Formula	Wavelength Range λ (μm)	Bandgap Energy W_g (eV)
Indium Phosphide	InP	0.92	1.35
Indium Arsenide	InAs	3.6	0.34
Gallium Phosphide	GaP	0.55	2.24
Gallium Arsenide	GaAs	0.87	1.42
Aluminium Arsenide	AlAs	0.59	2.09
Gallium Indium Phosphide	GaInP	0.64-0.68	1.82-1.94
Aluminium Gallium Arsenide	AlGaAs	0.8-0.9	1.4-1.55
Indium Gallium Arsenide	InGaAs	1.0-1.3	0.95-1.24
Indium Gallium Arsenide Phosphide	InGaAsP	0.9-1.7	0.73-1.35

SEMICONDUCTOR LIGHT-EMITTING DIODES

- **Semiconductor LEDs emit incoherent light.**
- **Spontaneous emission of light in semiconductor LEDs produces light waves that lack a fixed-phase relationship. Light waves that lack a fixed-phase relationship are referred to as incoherent light**

SEMICONDUCTOR LIGHT-EMITTING DIODES Cont…

- **The use of LEDs in single mode systems is severely limited because they emit unfocused incoherent light.**
- **Even LEDs developed for single mode systems are unable to launch sufficient optical power into single mode fibers for many applications.**
- **LEDs are the preferred optical source for multimode systems because they can launch sufficient power at a lower cost than semiconductor LDs.**

Spontaneous Emission

- **Spontaneous emission is the random generation of photons within the active layer of the LED. The emitted photons move in random directions. Only a certain percentage of the photons exit the semiconductor and are coupled into the fiber. Many of the photons are absorbed by the LED materials and the energy dissipated as heat.**

LIGHT-EMITTING DIODES

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Types of LED

The basic LED types used for fiber optic communication systems are

- **Surface-emitting LED (SLED),**
- **Edge-emitting LED (ELED), and**

LED performance differences (1)

- LED performance differences help link designers decide which device is appropriate for the intended application.
- For short-distance (0 to 3 km), low-data-rate fiber optic systems, SLEDs and ELEDs are the preferred optical source.
- Typically, SLEDs operate efficiently for bit rates up to 250 megabits per second (Mb/s). Because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.

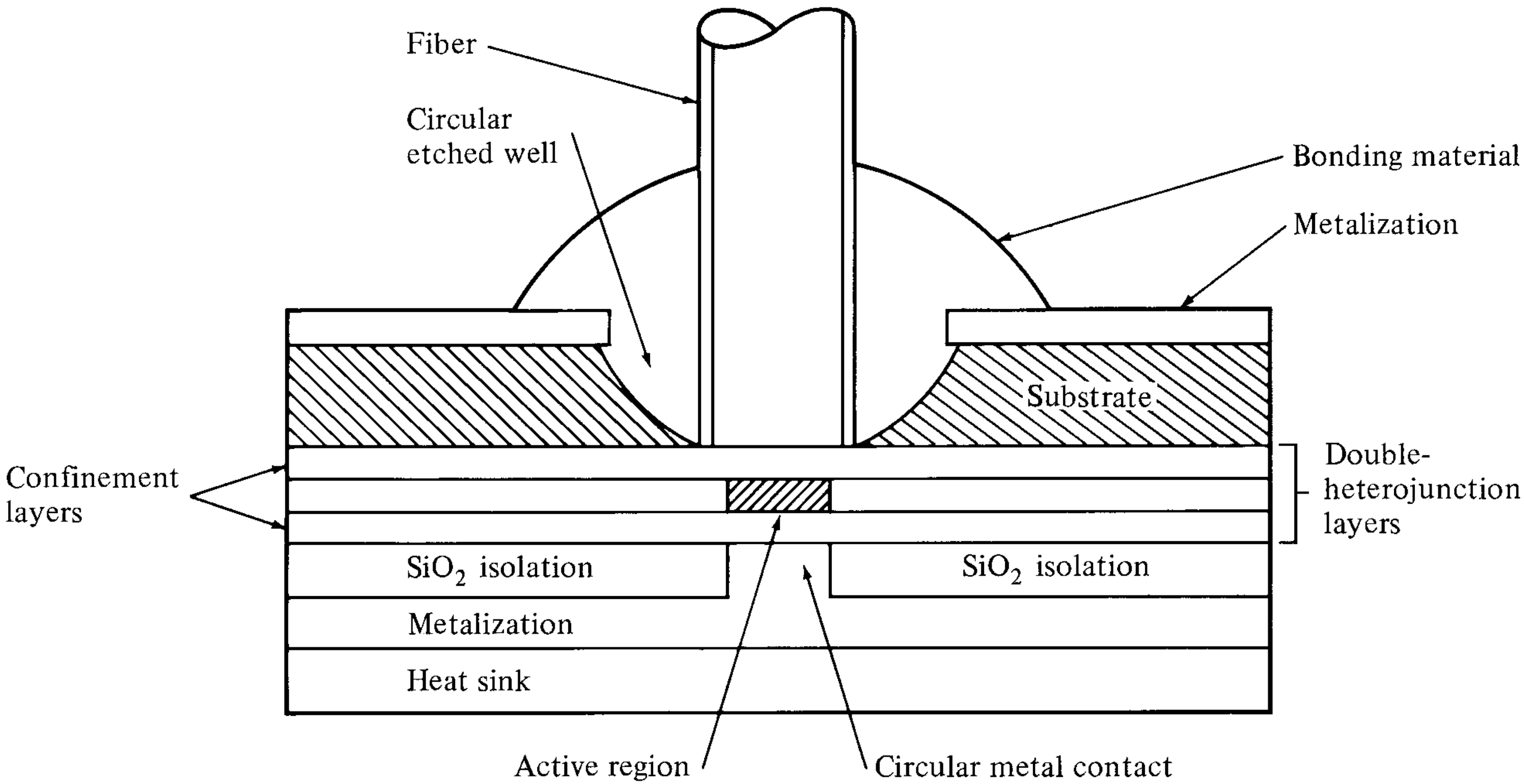
LED performance differences (2)

- **For medium-distance, medium-data-rate systems, ELEDs are preferred.**
- **ELEDs may be modulated at rates up to 400 Mb/s. ELEDs may be used for both single mode and multimode fiber systems.**

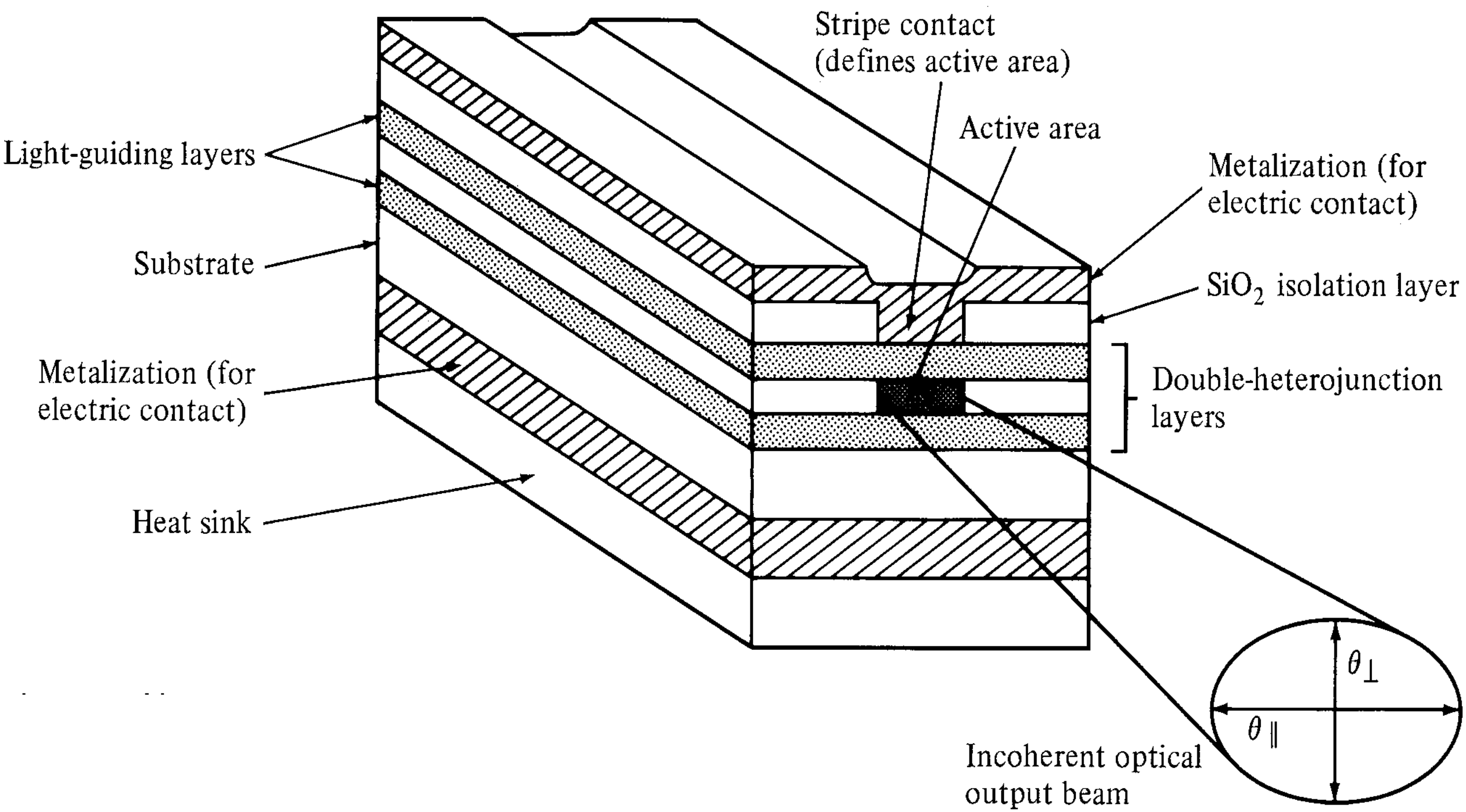
Surface-Emitting LEDs

- The surface-emitting LED is also known as the Burrus LED in honor of C. A. Burrus, its developer.
- In SLEDs, the size of the primary active region is limited to a small circular area of 20 μm to 50 μm in diameter.2.5 μm thick
- The active region is the portion of the LED where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.
- A well is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.

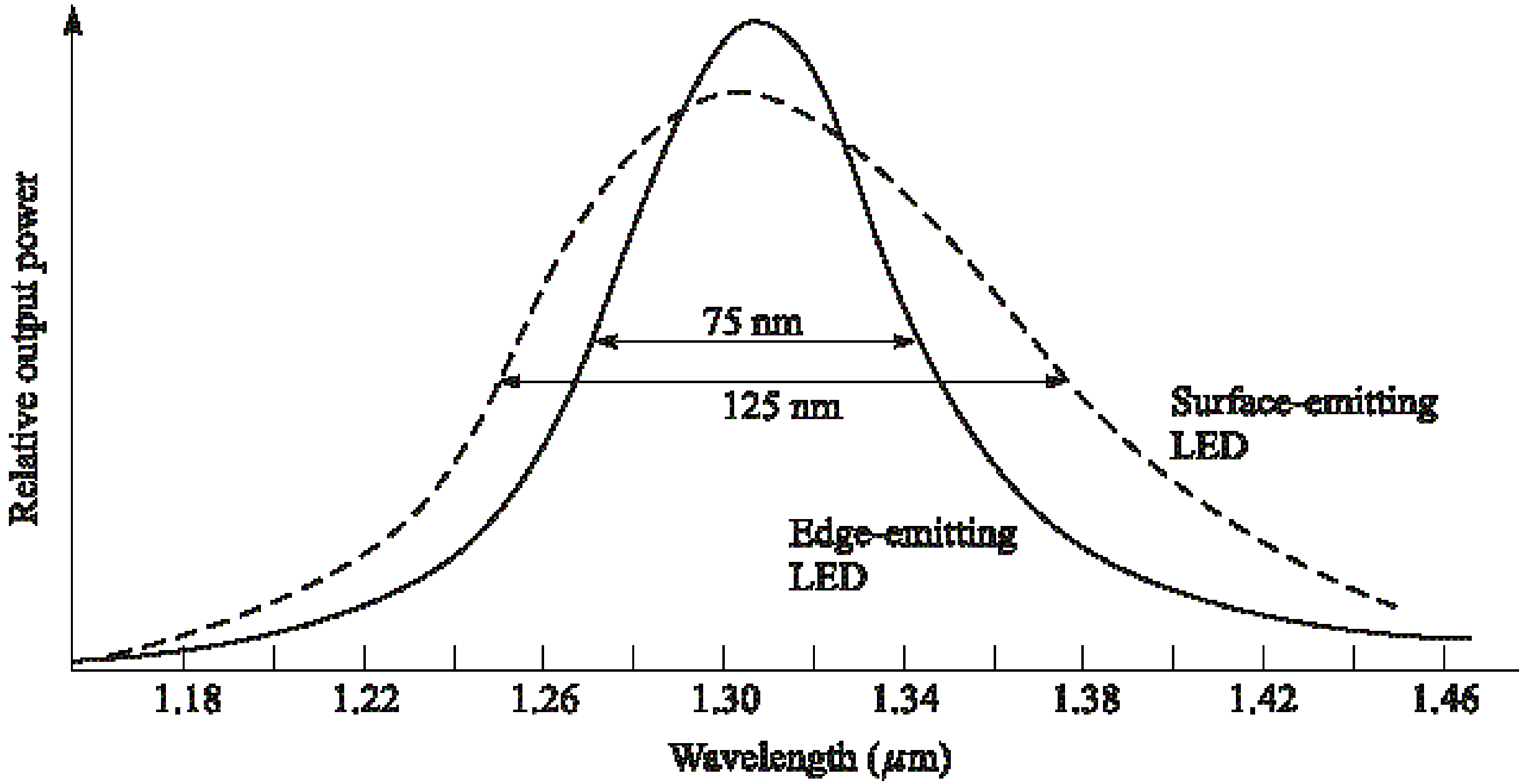
Surface-emitting LED



Edge-emitting LED

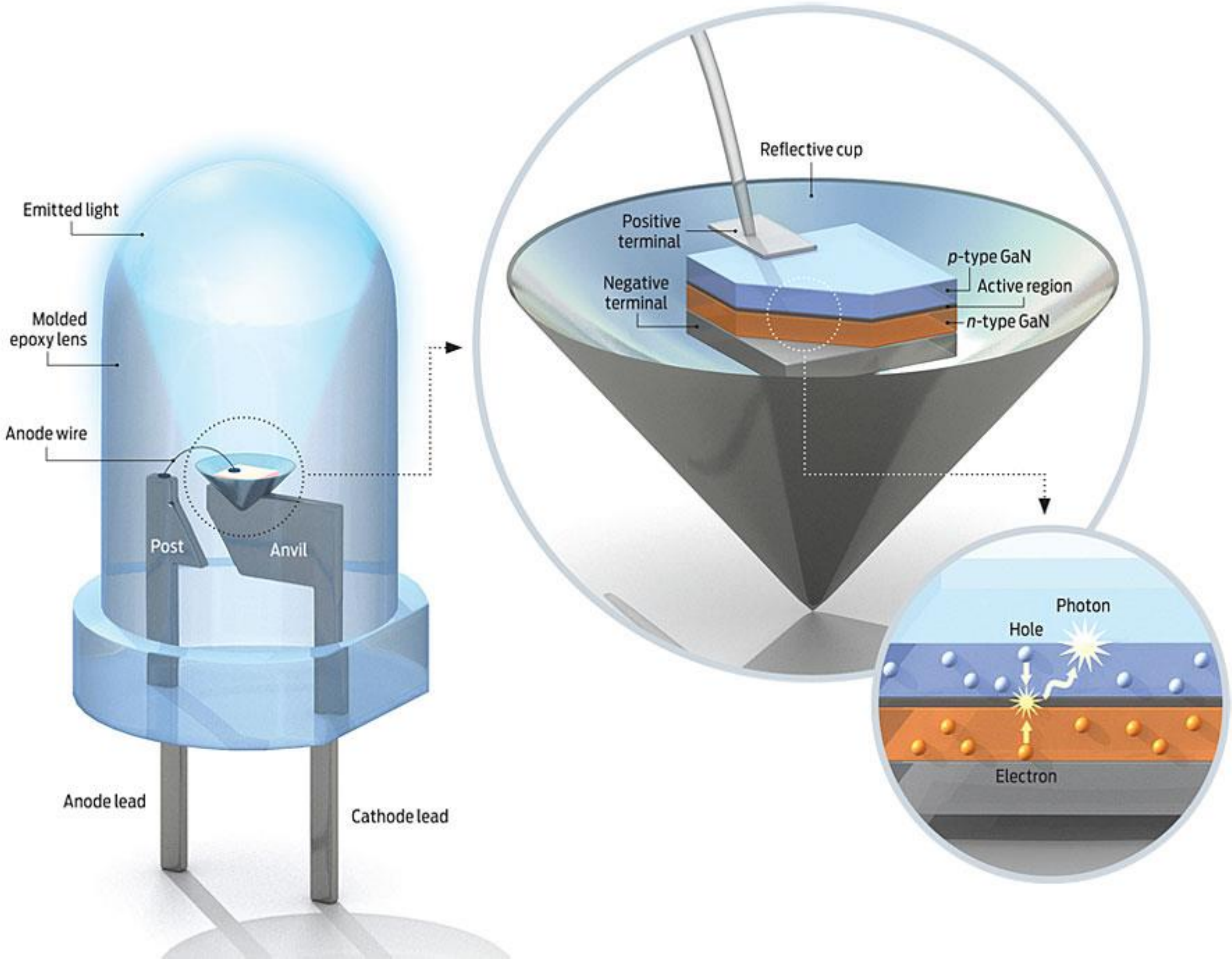


LED Spectral Width



Edge emitting LED's have slightly narrow line width

LIGHT EMITTING DIODES



Quantum Efficiency

- Internal quantum efficiency is the ratio between the radiative recombination rate and the sum of radiative and nonradiative recombination rates

$$\eta_{\text{int}} = R_r / (R_r + R_{nr})$$

- For exponential decay of excess carriers, the radiative recombination lifetime is n/R_r and the nonradiative recombination lifetime is n/R_{nr}

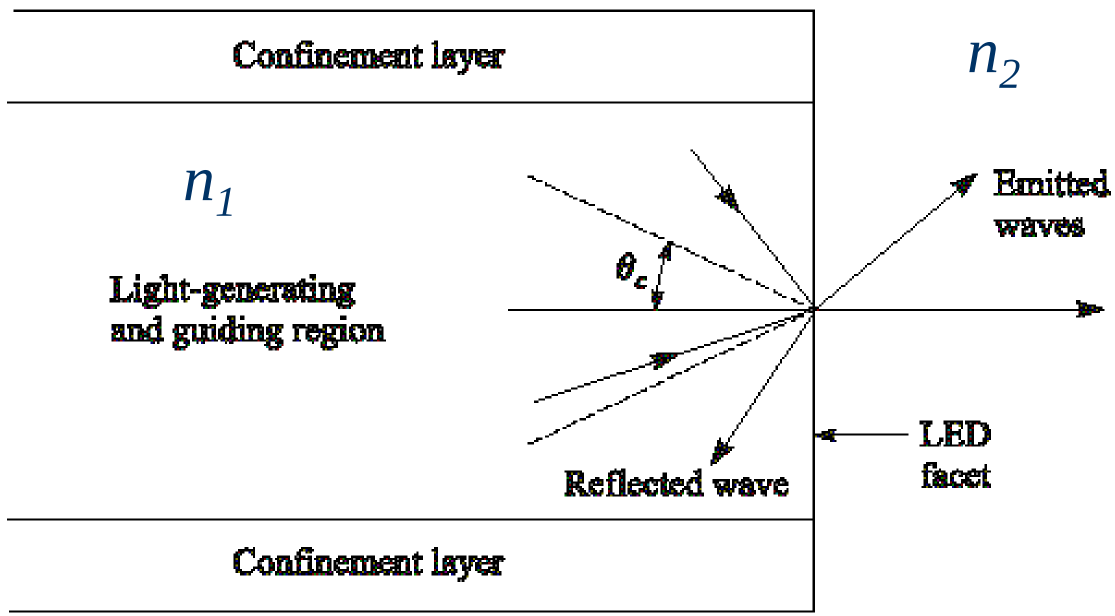
Internal Efficiency

- If the current injected into the LED is I, then the total number of recombination per second is, $R_r+R_{nr} = I/q$ where, q is the charge of an electron.
- That is, $R_r = \eta_{int} I/q$.
- Since R_r is the total number of photons generated per second, the optical power generated internal to the LED depends on the internal quantum efficiency

Optical power

- $P_{int} = \eta_{int} I/q\ h\nu = \eta_{int} Ihc/qlambda$

External Efficiency



Light emission cone

Fresnel Transmission Coefficient

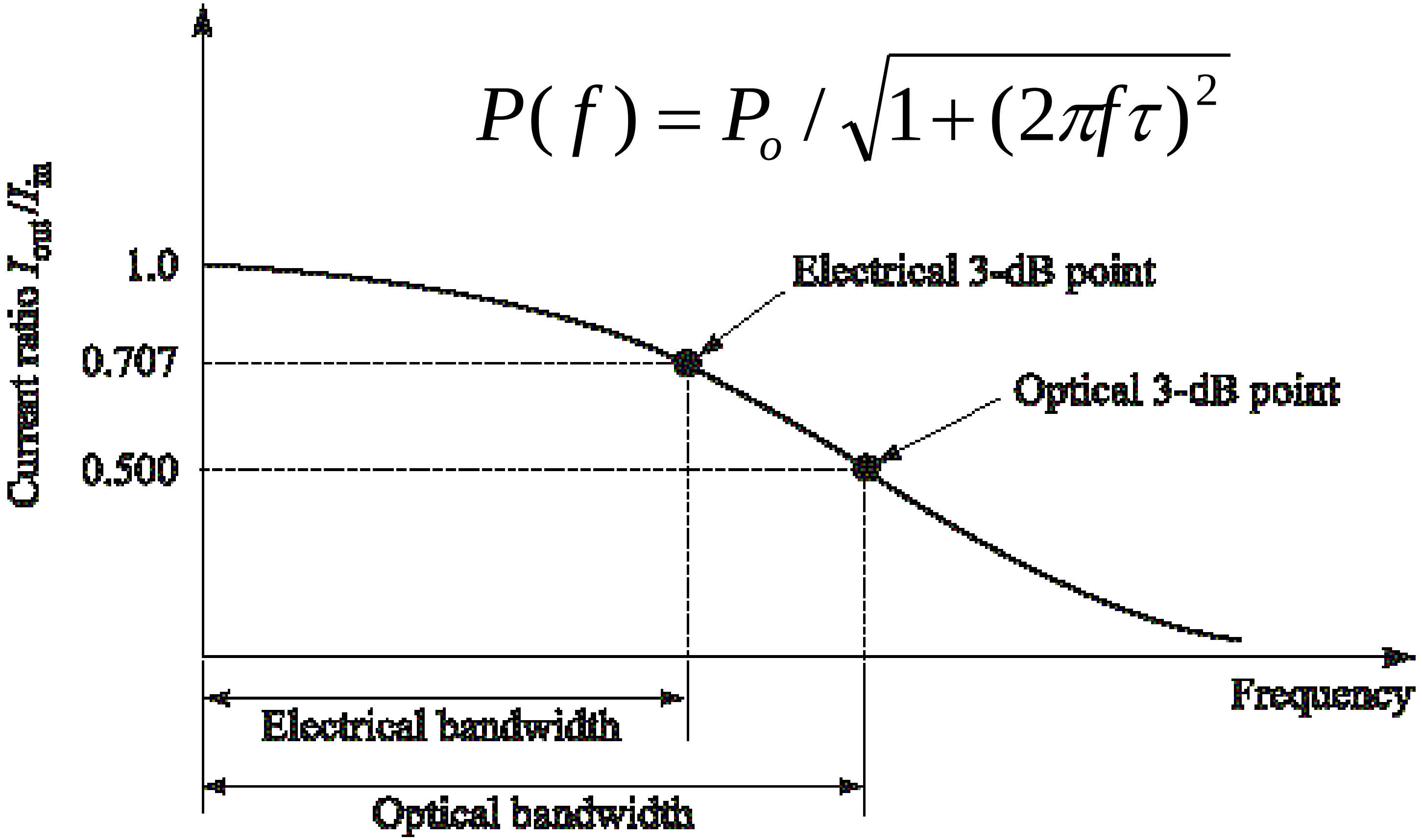
$$T(0) = \frac{4n_1 n_2}{(n_1 + n_2)^2}$$

External Efficiency for air

$n_2 = 1$, $n_1 = n$

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

3-dB bandwidths



Optical Power $\propto$ I(f); Electrical Power $\propto I^2(f)$

Electrical Loss = 2 x Optical Loss

Drawbacks of LED

- Large line width (30-40 nm)
- Large beam width (Low coupling to the fiber)
- Low output power
- Low E/O conversion efficiency

Advantages

- Robust
- Linear

Semiconductor LDs

- **Semiconductor LDs emit coherent light.**
- **LDs produce light waves with a fixed-phase relationship (both spatial and temporal) between points on the electromagnetic wave.**
- **Light waves having a fixed-phase relationship are referred to as coherent light.**

Semiconductor LDs Cont..

- **Semiconductor LDs emit more focused light than LEDs, they are able to launch optical power into both single mode and multimode optical fibers.**
- **LDs are usually used only in single mode fiber systems because they require more complex driver circuitry and cost more than LEDs.**

Produced Optical Power

- **Optical power produced by optical sources can range from microwatts (μW) for LEDs to tens of milliwatts (mW) for semiconductor LDs.**
- **However, it is not possible to effectively couple all the available optical power into the optical fiber for transmission.**

Dependence of coupled power

The amount of optical power coupled into the fiber is the relevant optical power. It depends on the following factors:

- ***The angles over which the light is emitted***
- ***The size of the source's light-emitting area relative to the fiber core size***
- ***The alignment of the source and fiber***
- ***The coupling characteristics of the fiber (such as the NA and the refractive index profile)***

- **Typically, semiconductor lasers emit light spread out over an angle of 10 to 15 degrees.**
- **Semiconductor LEDs emit light spread out at even larger angles.**
- **Coupling losses of several decibels can easily occur when coupling light from an optical source to a fiber, especially with LEDs.**
- **Source-to-fiber coupling efficiency is a measure of the relevant optical power.**
- **The coupling efficiency depends on the type of fiber that is attached to the optical source.**
- **Coupling efficiency also depends on the coupling technique.**

- **Current flowing through a semiconductor optical source causes it to produce light.**
- **LEDs generally produce light through spontaneous emission when a current is passed through them.**

The LASER

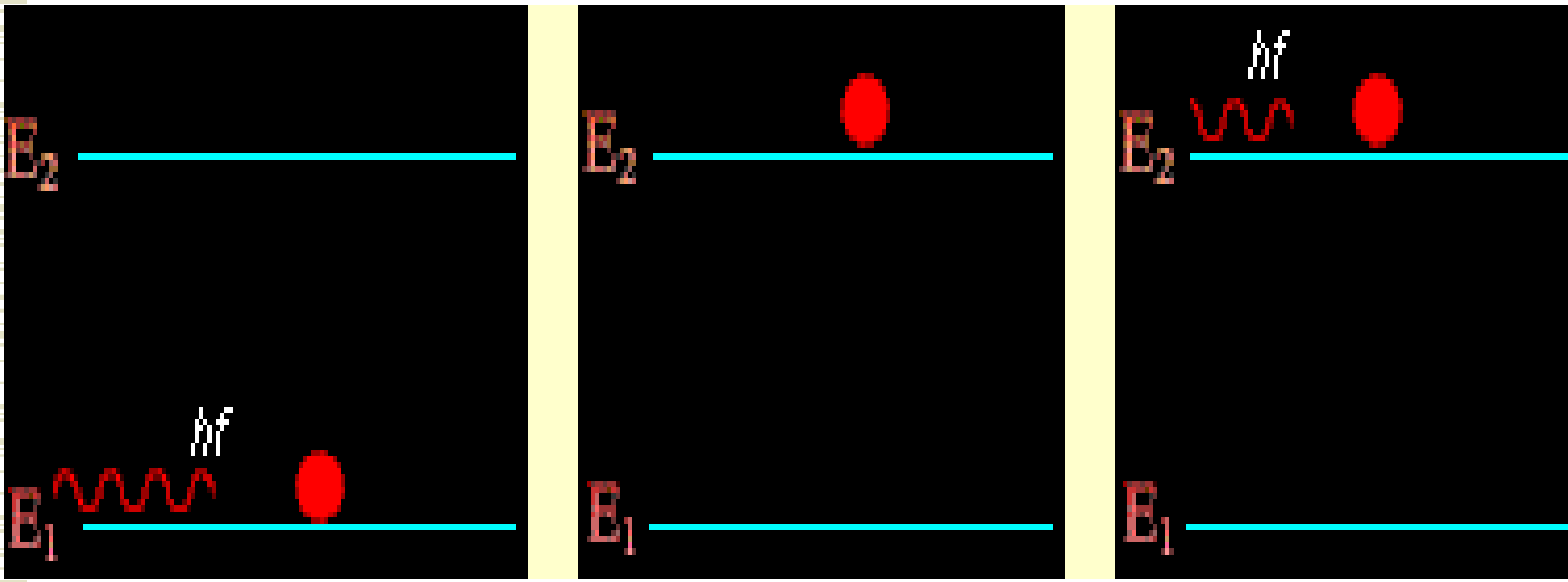
- Light Amplification by ‘Stimulated Emission’ and Radiation (L A S E R)
- Coherent light (stimulated emission)
- Narrow beam width (very focused beam)
- High output power (amplification)
- Narrow line width because only few wavelength will experience a positive feedback and get amplified (optical filtering)

The LASER

- The semiconductor laser differs from other lasers (solid, gas, and liquid lasers):
  - small size (typical on the order of $0.1 \times 0.1 \times 0.3$ mm^3)
  - high efficiency
  - the laser output is easily modulated at high frequency by controlling the junction current
  - low or medium power (as compared with ruby or CO_2 laser, but is comparable to the He-Ne laser)
  - particularly suitable for fiber optic communication

Fundamental Lasing Operation

- **Absorption:** An atom in the ground state might absorb a photon emitted by another atom, thus making a transition to an excited state.
- **Spontaneous Emission:** Random emission of a photon, which enables the atom to relax to the ground state.
- **Stimulated Emission:** An atom in an excited state might be stimulated to emit a photon by another incident photon.

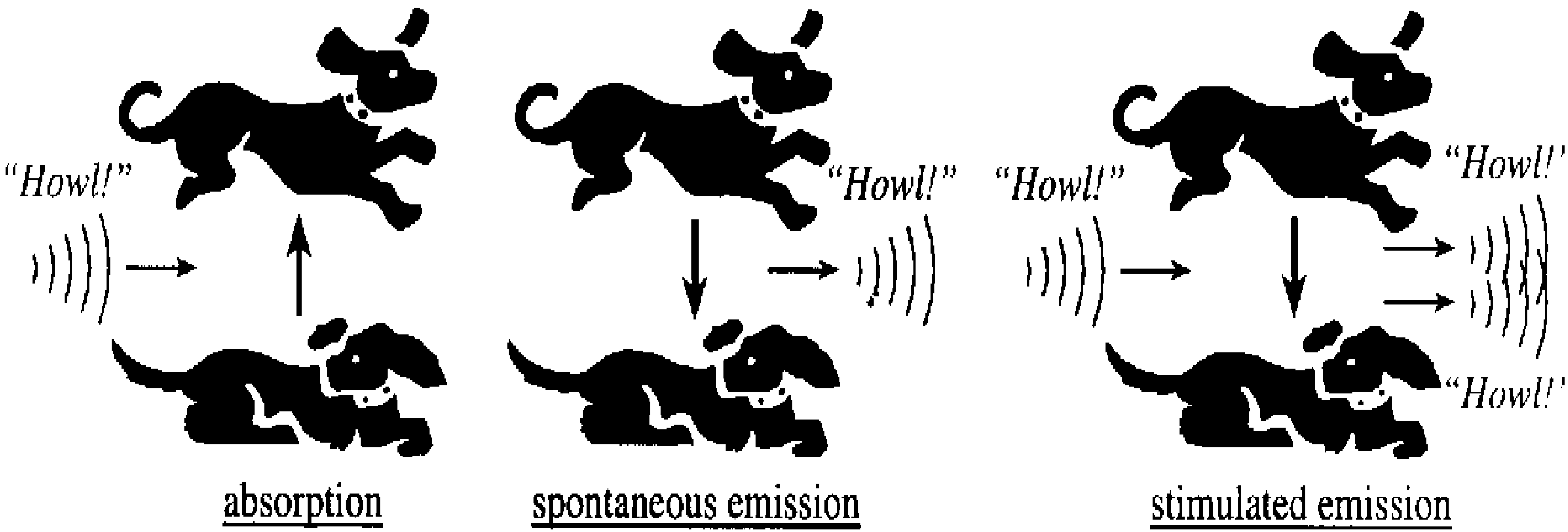

E_2
E_1
$h\nu$
E_2
E_1
E_2
$h\nu$
E_1

Howling Dog Analogy

1. <u>absorption</u>: a dog in the ground state might hear the howl from another dog and become excited, thus making a transition to the excited state.

2. <u>spontaneous emission</u>: a dog in the excited state might randomly let out a howl, which, through release of tension, enables him to relax to the ground state.

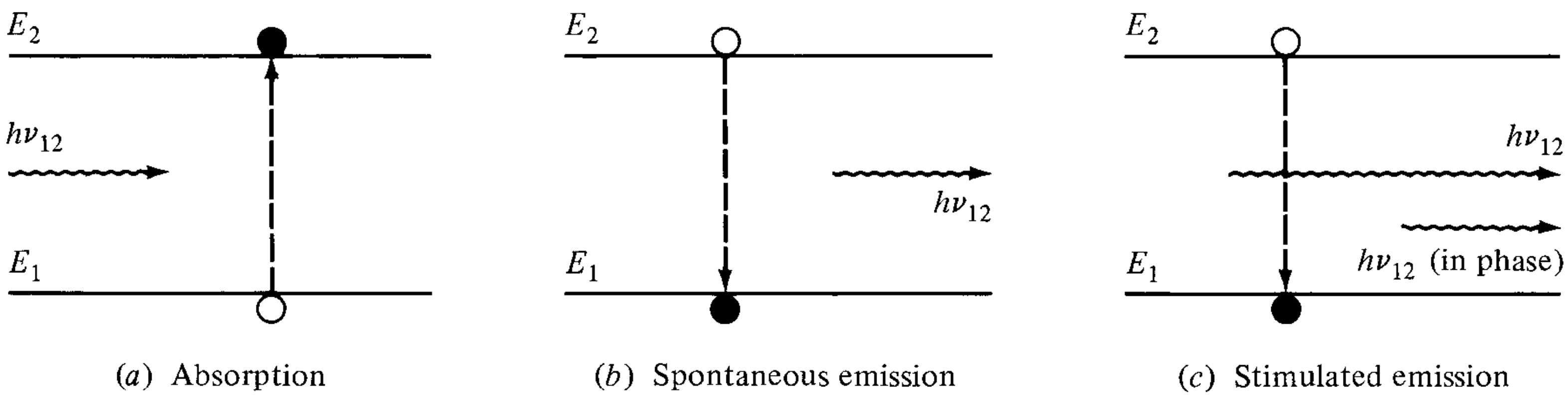
3. <u>stimulated emission</u>: a dog in the excited state might be stimulated to let out a howl when he hears the howl from another dog. The single howl becomes two howls voiced simultaneously, thus sounding like one howl with twice the intensity!



In Stimulated Emission incident and stimulated photons will have

- Identical energy → Identical wavelength → Narrow linewidth
- Identical direction → Narrow beam width
- Identical phase → Coherence and
- Identical polarization

Laser Transition Processes (Stimulated and Spontaneous Emission)

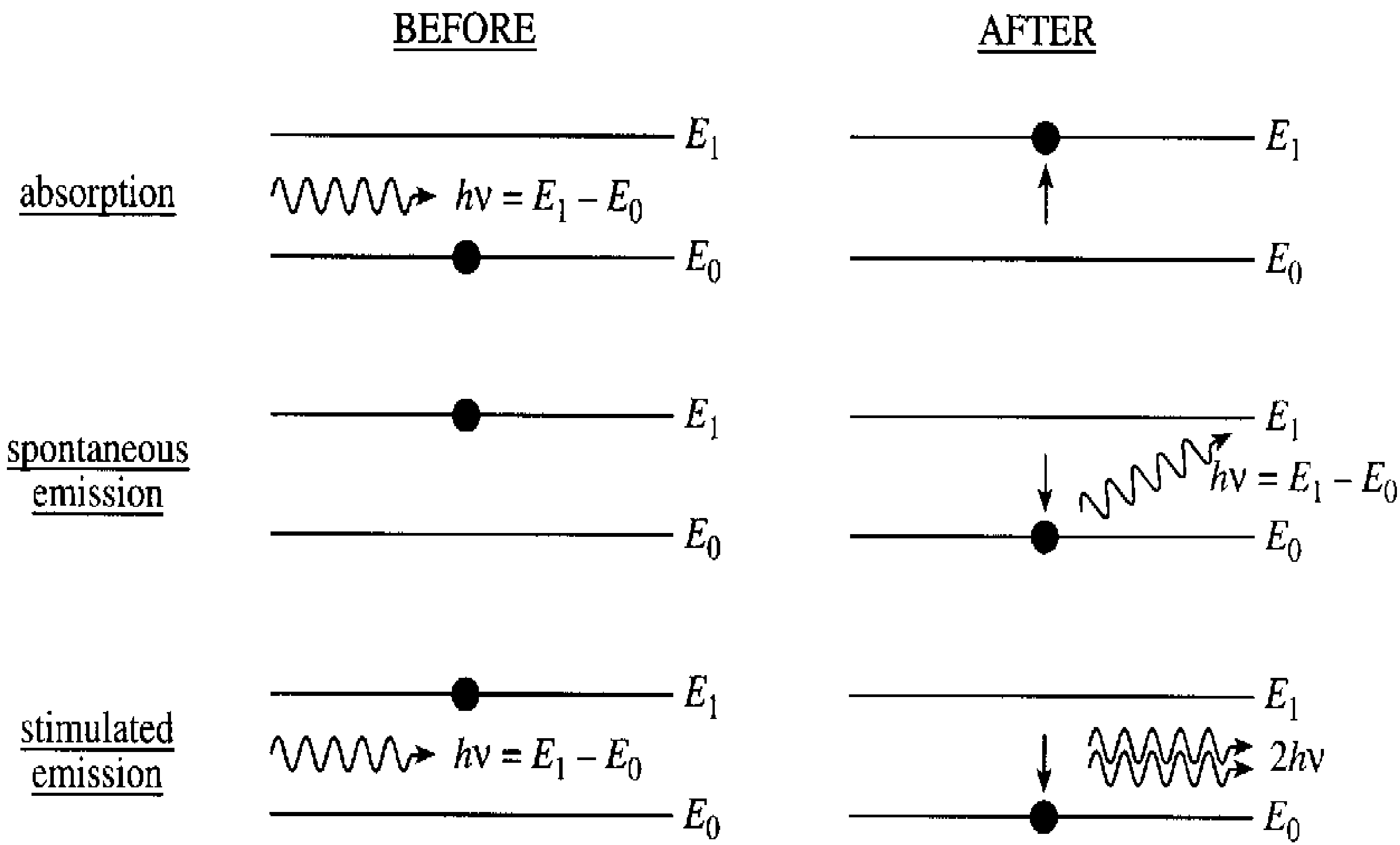


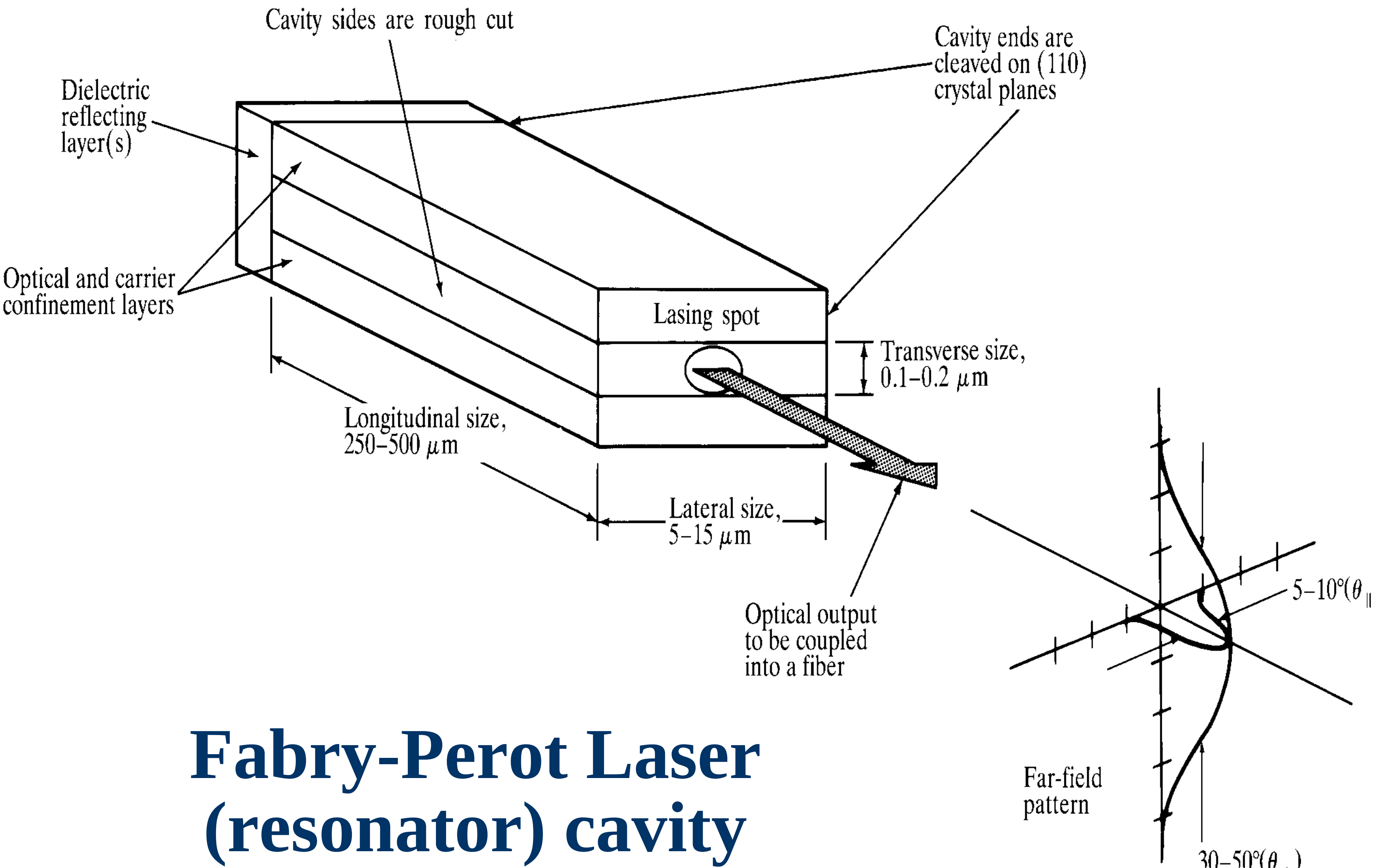
Energy absorbed from the incoming photon

Random release of energy

Coherent release of energy

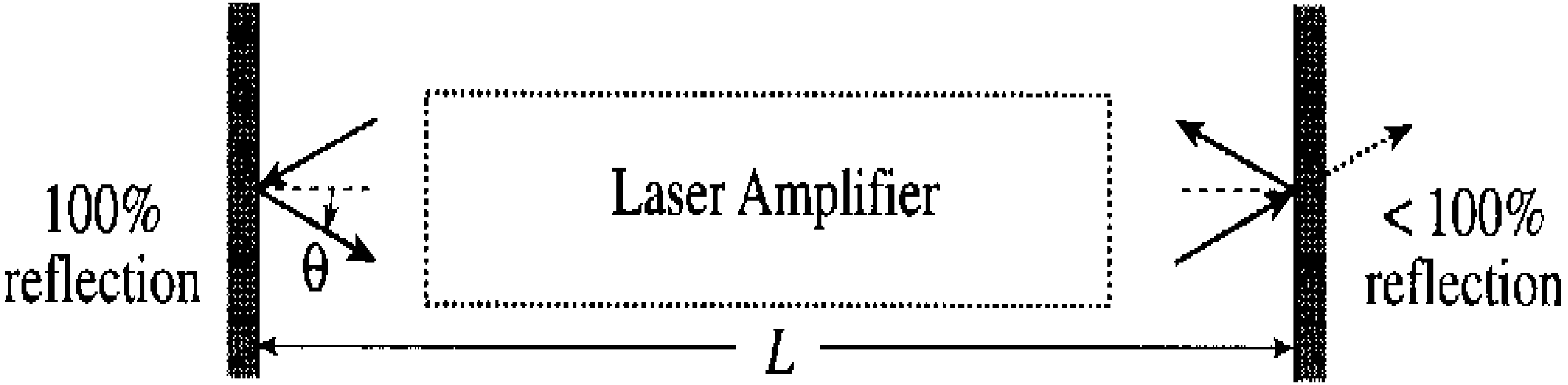
Stimulated Emission



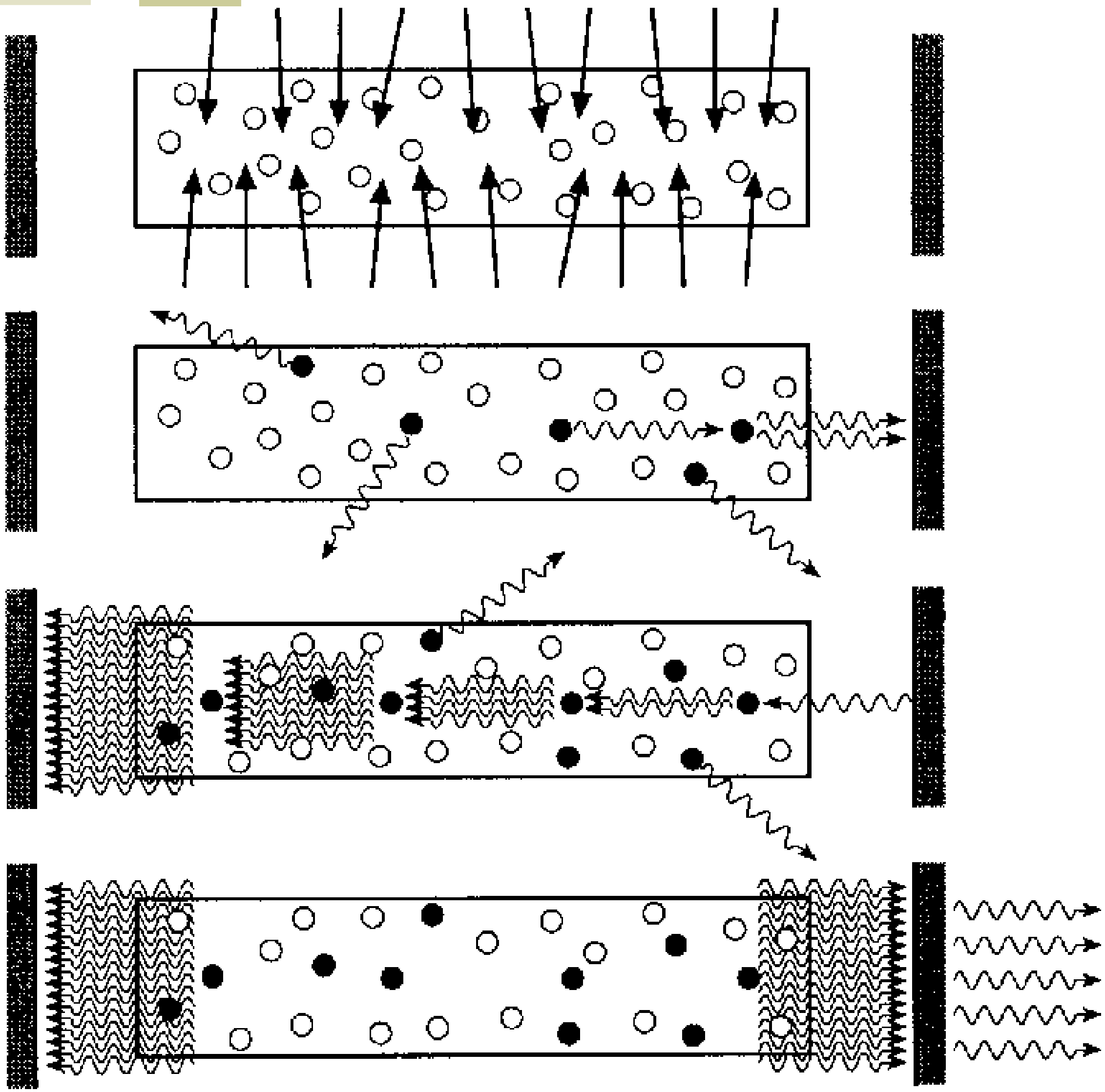


Fabry-Perot Laser (resonator) cavity

Mirror Reflections



How a Laser Works



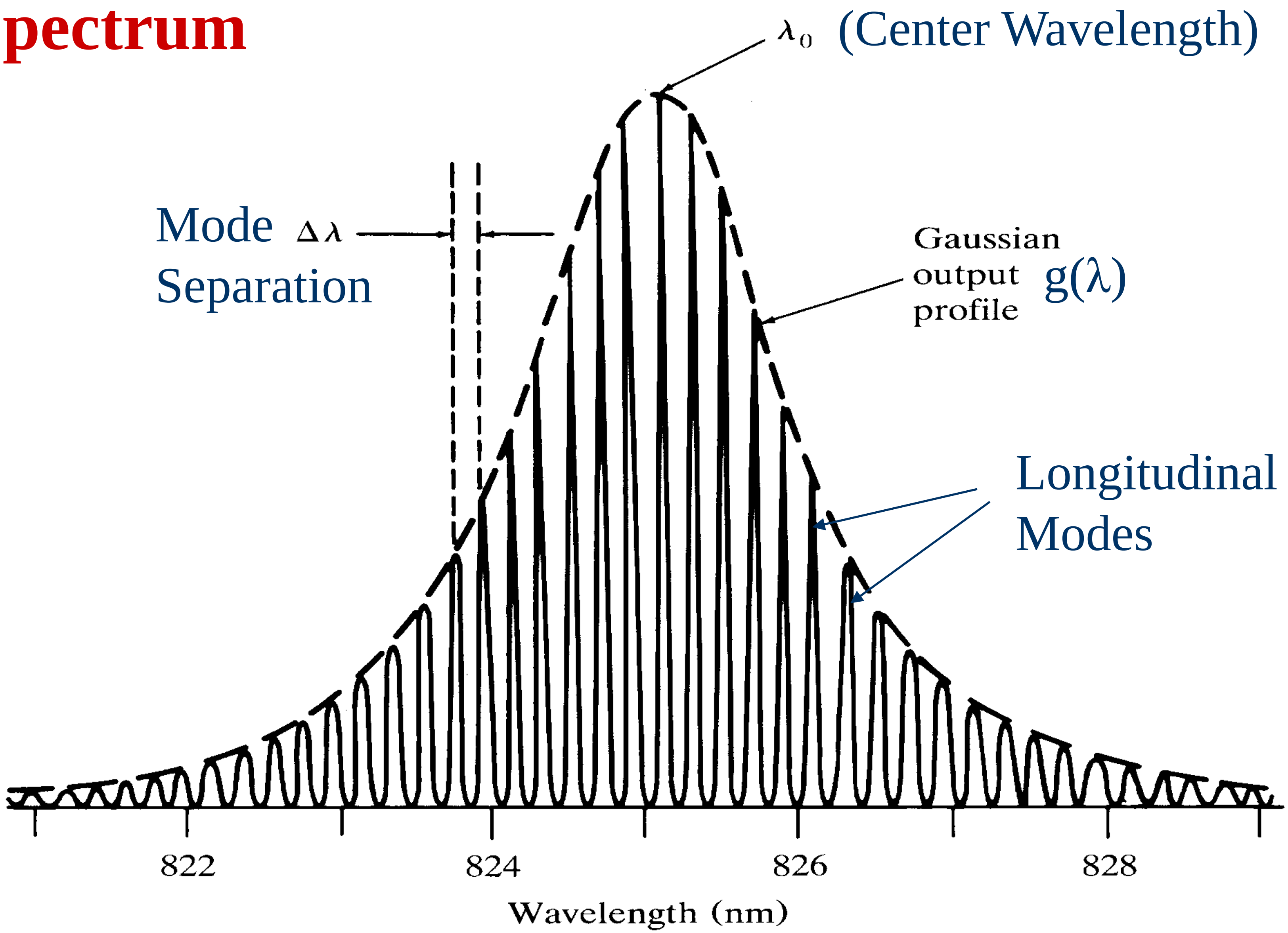
pump on
○ = atoms in excited state

spontaneous emission &
rare stimulated emission

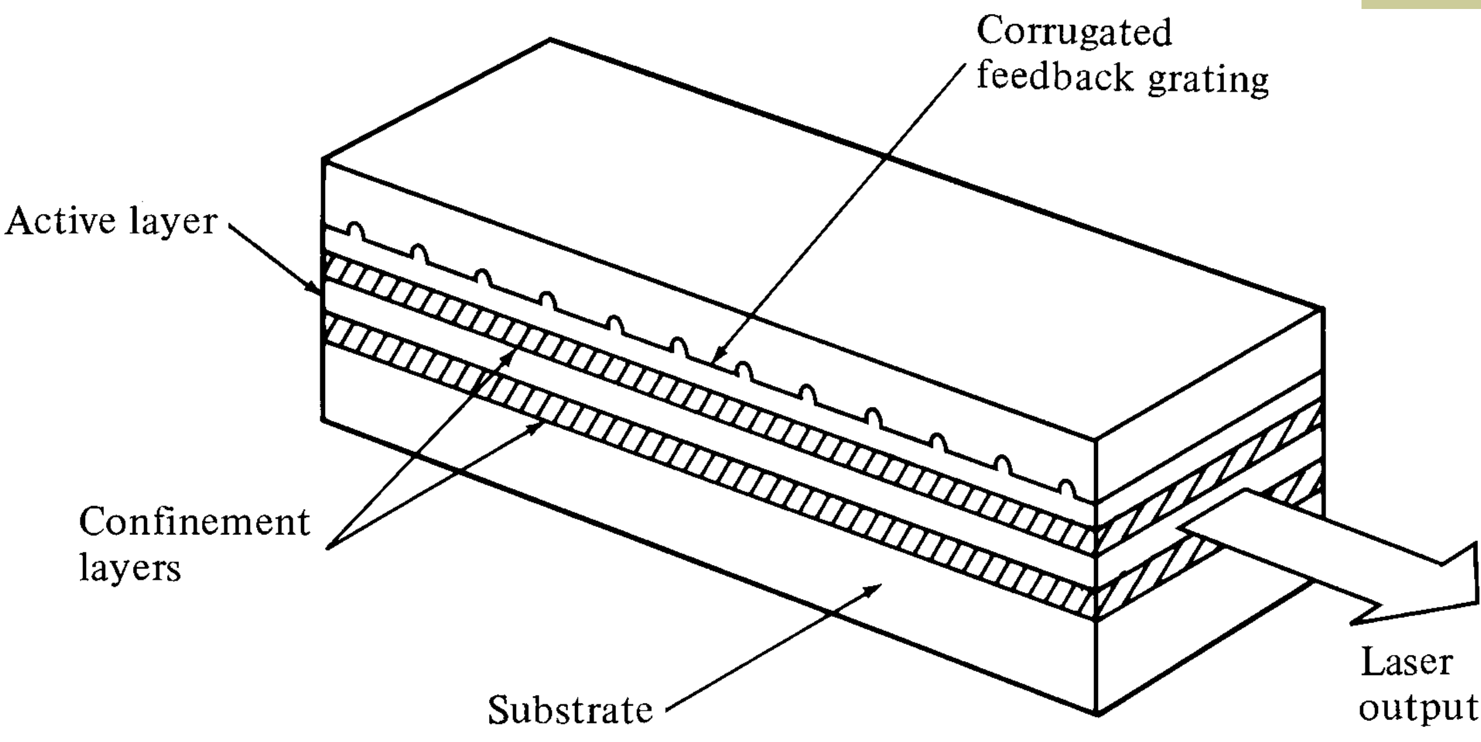
stimulated emission of
light along the laser axis

steady-state
laser operation

Multimode Laser Output Spectrum



Distributed Feedback Laser (Single Mode Laser)



The optical feedback is provided by fiber Bragg Gratings
→ Only one wavelength get positive feedback

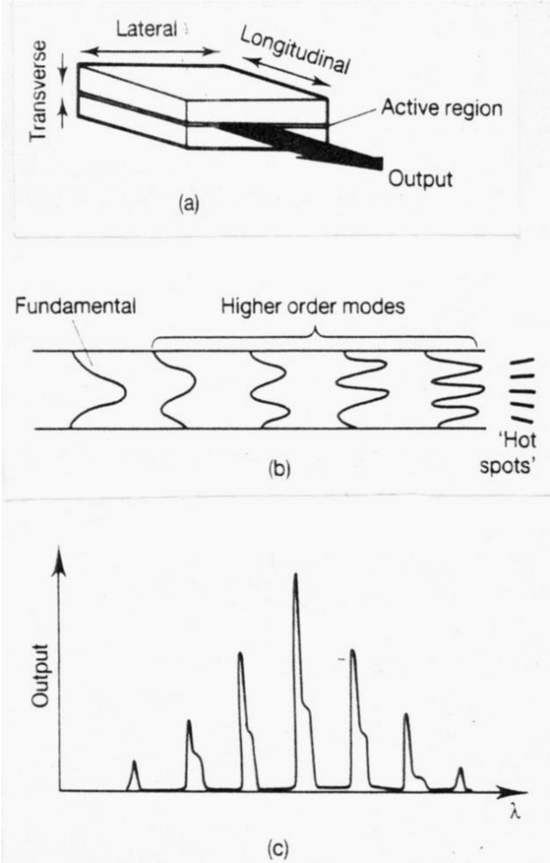
Resonant modes of a laser cavity

- ***Longitudinal modes***
  - determine the output-light wavelength
- ***Lateral modes***
  - leading to subpeaks on the sides of the fundamental modes, and resulting in "kinks" in the output-current curve.
  - suppressed by the "*stripe-geometry*" structure
- ***Transverse modes***
  - generating "hot spots"
  - suppressed by "thin active layer " design

➔ Suppressing lateral and transverse mode is necessary to improve the performance of lasers.

☞ ***Single-mode laser:*** the laser operates in the fundamental transverse and lateral modes but with several longitudinal modes.

☞ ***Single-frequency laser:*** the laser operates in only one longitudinal mode.



- we express the electromagnetic wave propagating in the longitudinal direction

$$E(z,t) = I(z)\, e^{j(\omega t - \beta z)}$$

$$I(z) = I(0)\exp\{[\Gamma g(h\nu) - \bar{\alpha}(h\nu)]\, z\}$$

$\bar{\alpha}$ - the effective absorption coefficient

g- the optical-fi eld confi nement factor

- Reflectivity of the mirror

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

$$I(2L) = I(0)\, R_1 R_2 \exp\{2L\,[\Gamma g(h\nu) - \bar{\alpha}(h\nu)]\}$$

- Lasing condition

$$I(2L) = I(0)$$

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

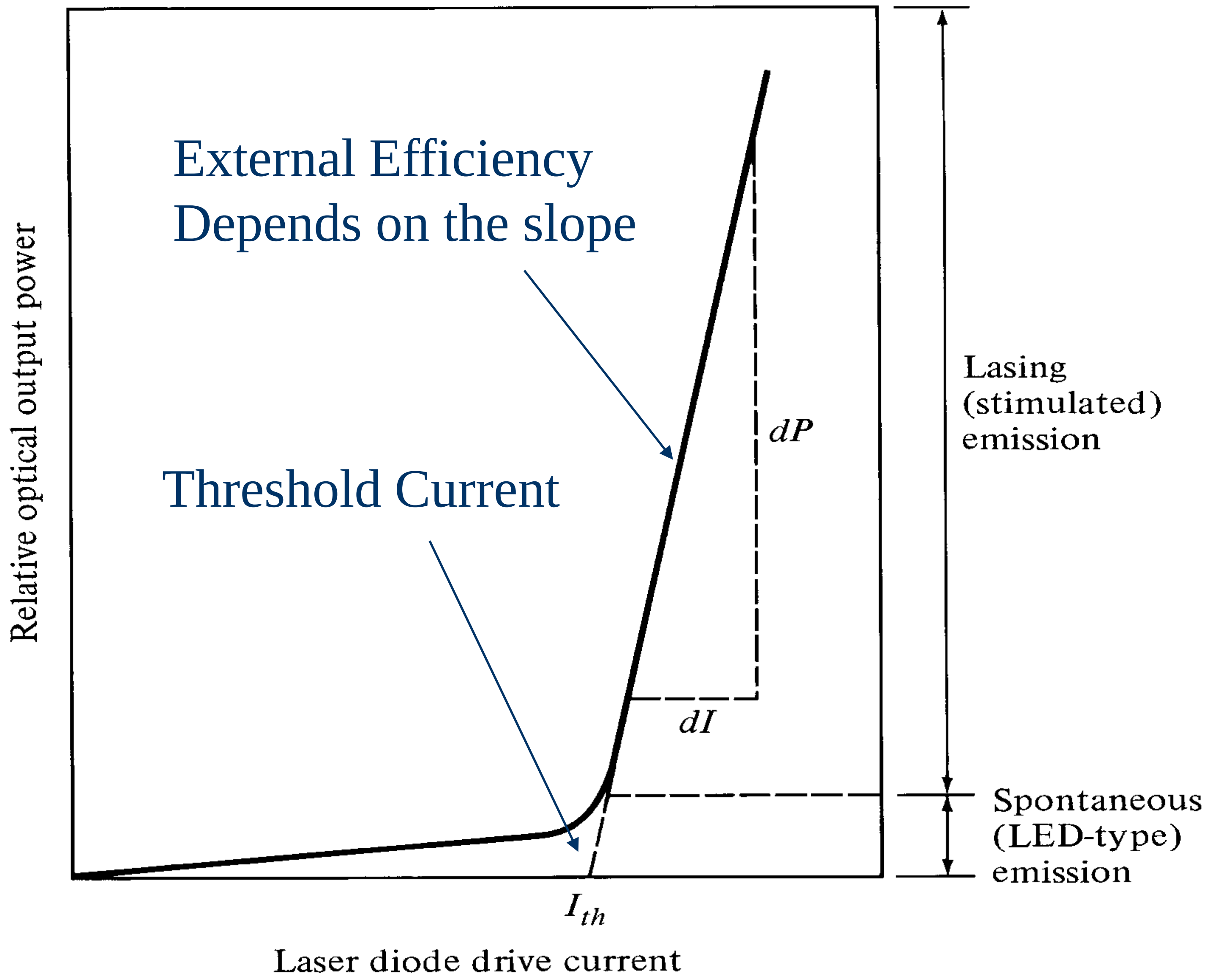
- The condition to just reach the lasing threshold is the point at which the optical gain is equal to the total loss at, in the cavity

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

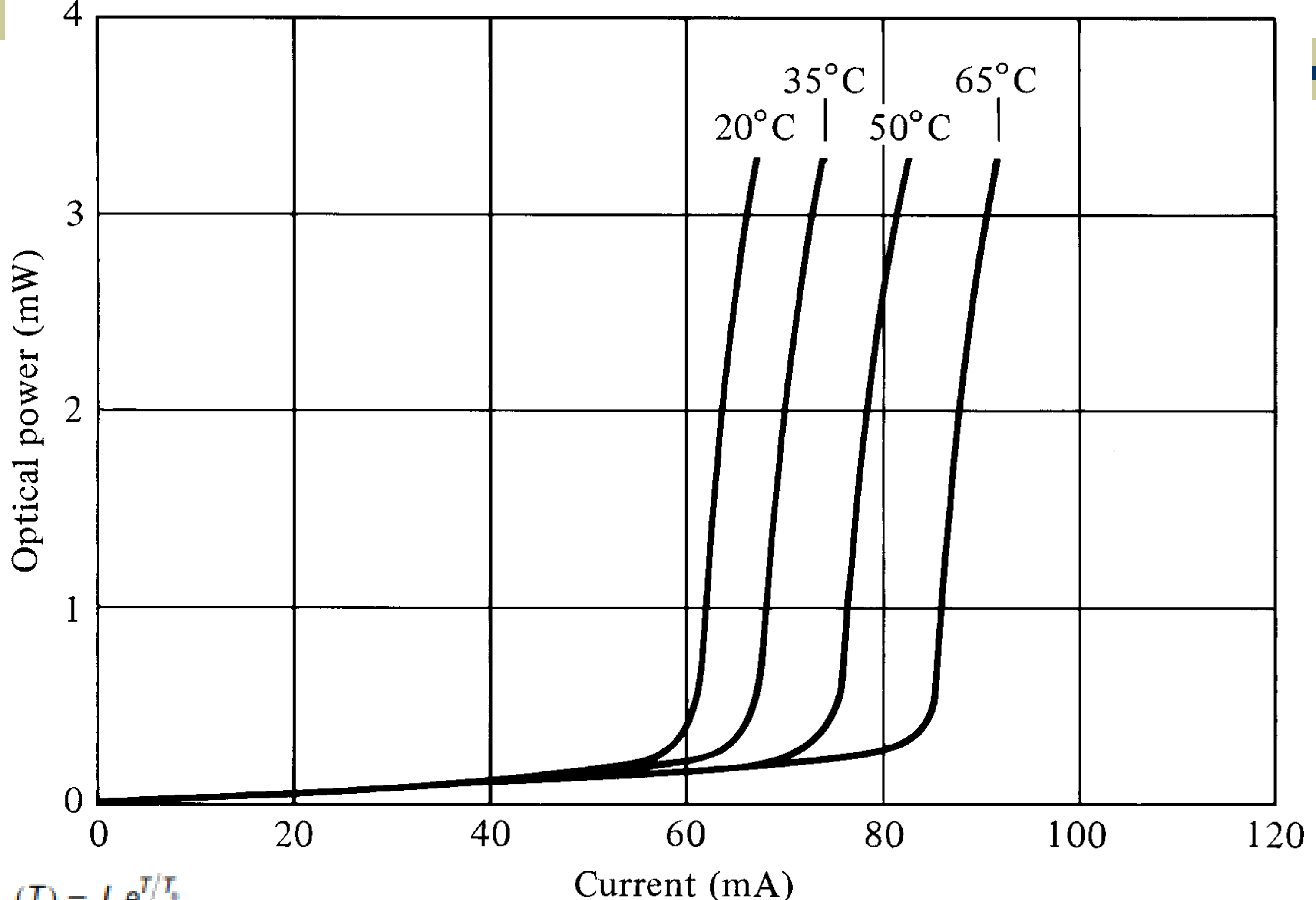
- Threshold current density

$$g_{\text{th}} = \overline{\beta} J_{\text{th}}$$

Optical output vs. drive current of a laser



Laser threshold depends on Temperature



$$I_{th}(T) = I_z e^{T/T_o}$$

Laser Diode Rate Equations

- The relationship between optical output power and the diode drive current can be determined by examining the rate equations that govern the interaction of photons and electrons in the active region.

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

$$= \text{stimulated emission} + \text{spontaneous emission} + \text{photon loss}$$

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

$$= \text{injection} + \text{spontaneous recombination} + \text{stimulated emission}$$

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

$n = n_{th}$ in the steady state when the number of photons $\Phi = 0$:

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

Rate Equation

The photon and electron rate equations in the steady-state condition at the lasing threshold.

$$0 = Cn_{th}\Phi_s + R_{sp} - \frac{\Phi_s}{\tau_{ph}}$$

$$0 = \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\Phi_s$$

the number of photons per unit volume

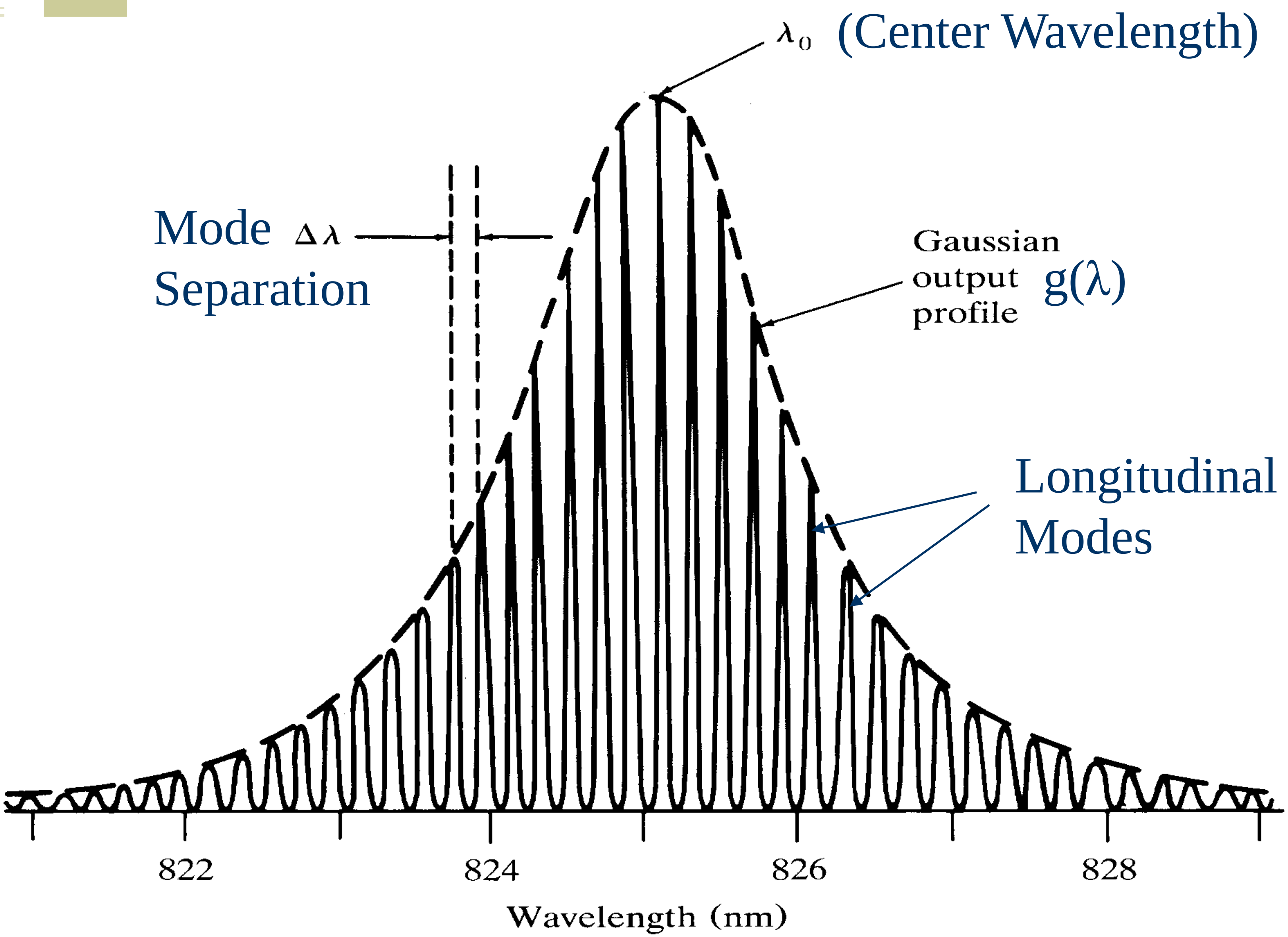
$$\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp}$$

External Quantum Efficiency

$$\eta_{\text{ext}} = \frac{\eta_i (g_{\text{th}} - \bar{\alpha})}{g_{\text{th}}}$$

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

Multimode Laser Output Spectrum



Laser Resonant Frequencies

- Lasing condition, namely eq. [4-22]:

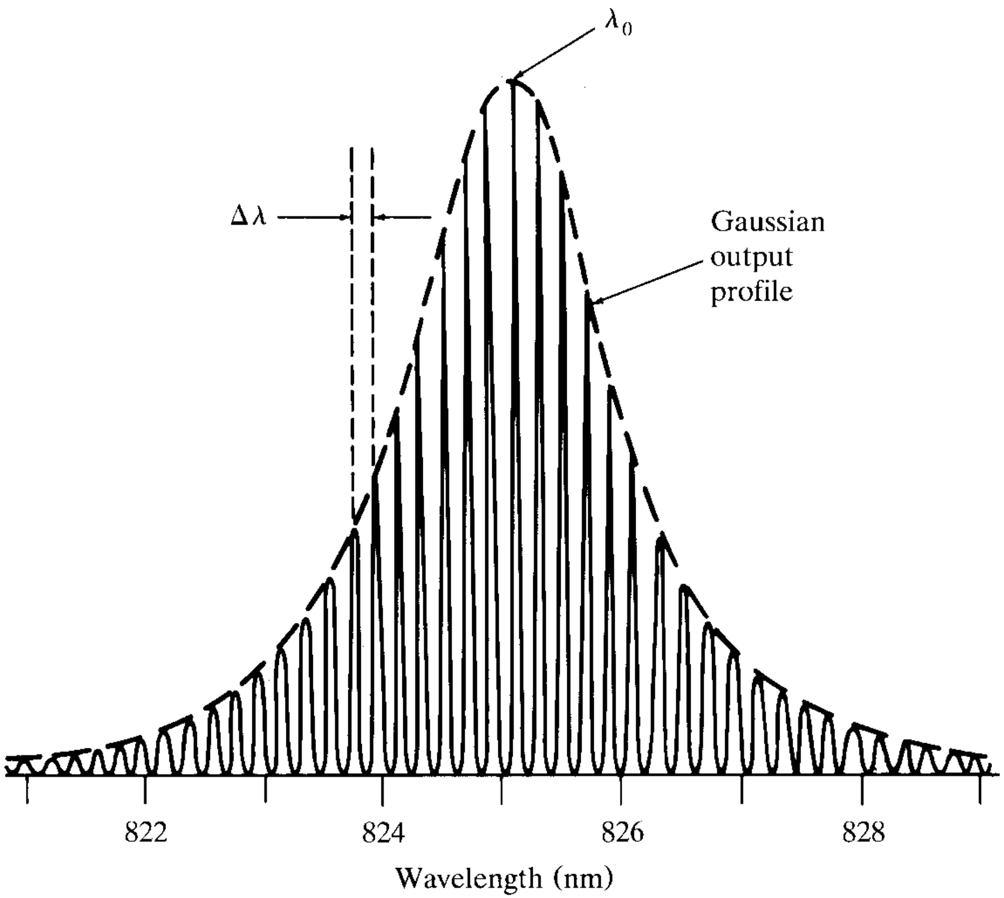
$$\exp(-j2\beta L)=1 \Rightarrow \qquad 2\beta L = 2m\pi, \quad m=1,2,3,\ldots$$

- Assuming $\beta = \dfrac{2\pi n}{\lambda}$ the resonant frequency of the *m*th mode is:

$$\boxed{\upsilon_m = \frac{mc}{2Ln}} \qquad m=1,2,3,\ldots \qquad \text{[4-30]}$$

$$\Delta\upsilon = \upsilon_m - \upsilon_{m-1} = \frac{c}{2Ln} \Leftrightarrow \boxed{\Delta\lambda = \frac{\lambda^2}{2Ln}} \qquad \text{[4-31]}$$

Spectrum from a laser Diode



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

[4-32]

Laser Diode Structure & Radiation Pattern

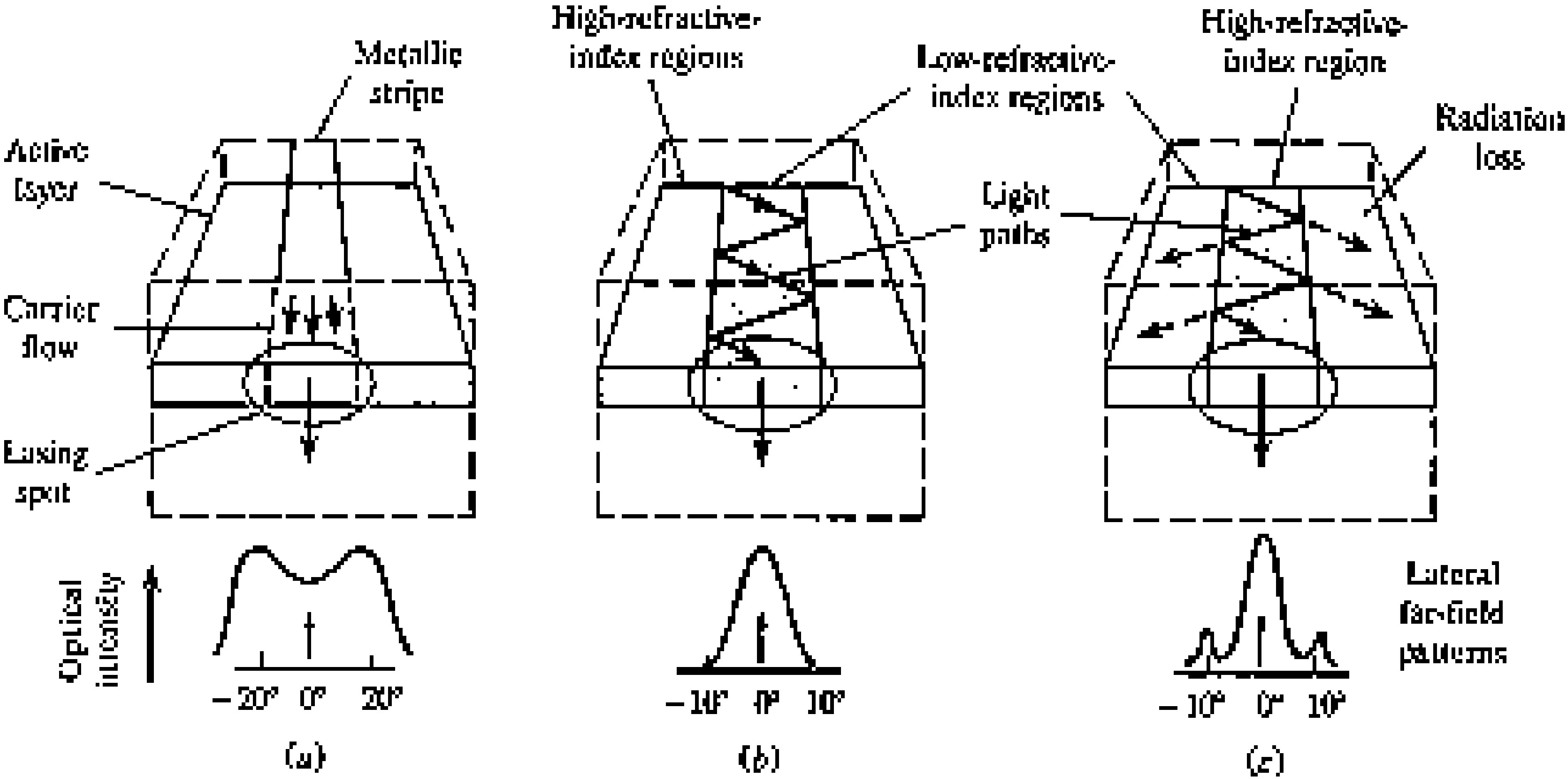
- Efficient operation of a laser diode requires reducing the # of lateral modes, stabilizing the gain for lateral modes as well as lowering the threshold current. These are met by structures that confine the optical wave, carrier concentration and current flow in the lateral direction. The important types of laser diodes are: **gain-induced, positive index guided, and negative index guided**.

Laser diode structure and ration pattern

Optical confinement Methods

gain guided laser
Index guided laser
Buried hetro structure
selective diffusion method
varying thickness
bent layer structure

current confinement method
preferential dopant method
proton implantation method
inner stripe confinement
regrowth of back biased pn junction



(a) gain-induced guide (b)positive-index waveguide (c)negative-index waveguide

Laser Diode with buried heterostructure (BH)

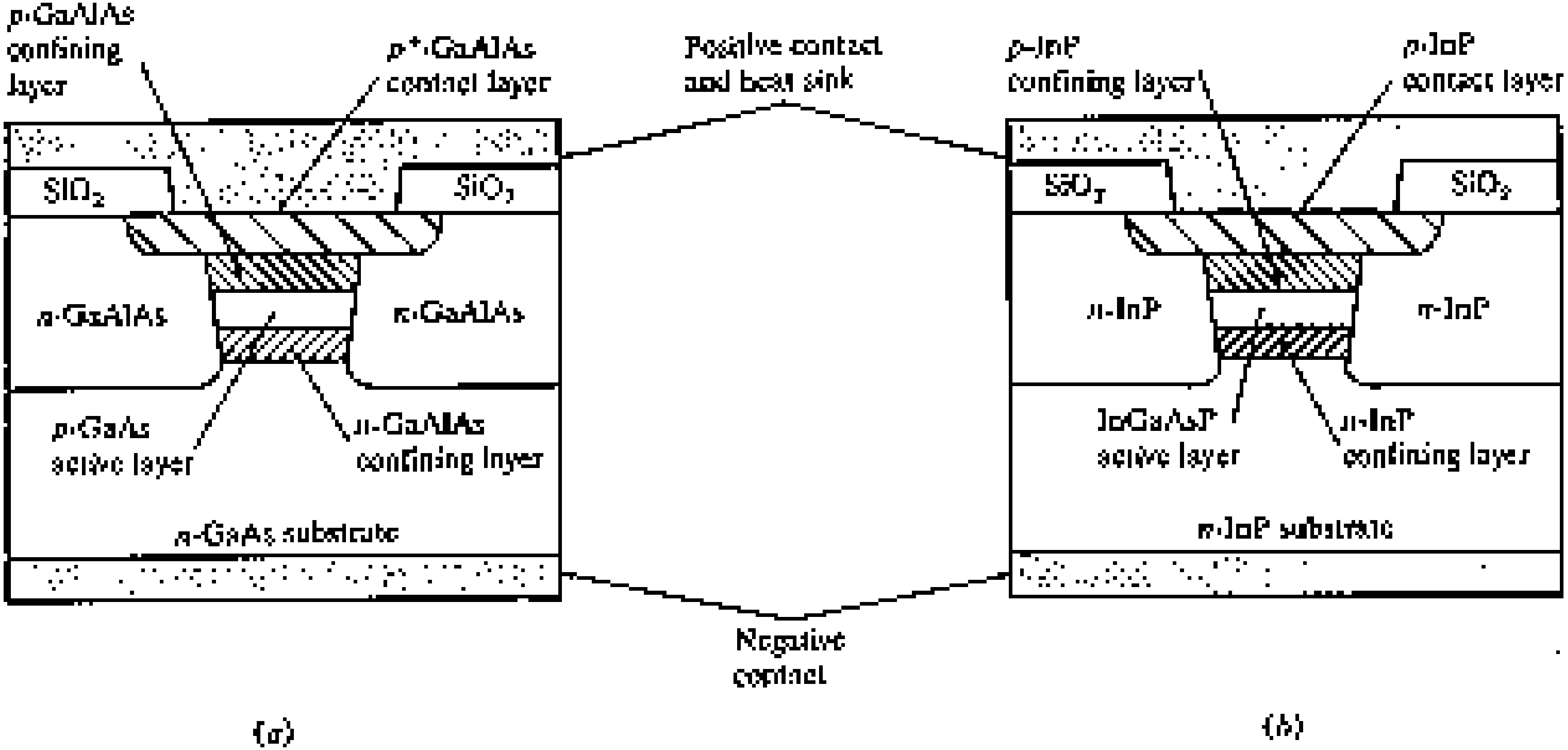


FIGURE 4-23
(*a*) Short-wavelength (800–900 nm) GaAlAs and (*b*) long-wavelengths (1300–1600 nm) InGaAsP buried-heterostructure laser diodes.

Single Mode Laser

- Single mode laser is mostly based on the index-guided structure that supports only the fundamental transverse mode and the fundamental longitudinal mode. In order to make single mode laser we have four options:

  1- Reducing the length of the cavity to the point where the frequency separation given in eq[4-31] of the adjacent modes is larger than the laser transition line width. This is hard to handle for fabrication and results in low output power.

  2- **Vertical-Cavity Surface Emitting laser (VCSEL)**

  3- Structures with built-in frequency selective grating

  4- tunable laser diodes

.

VCSEL

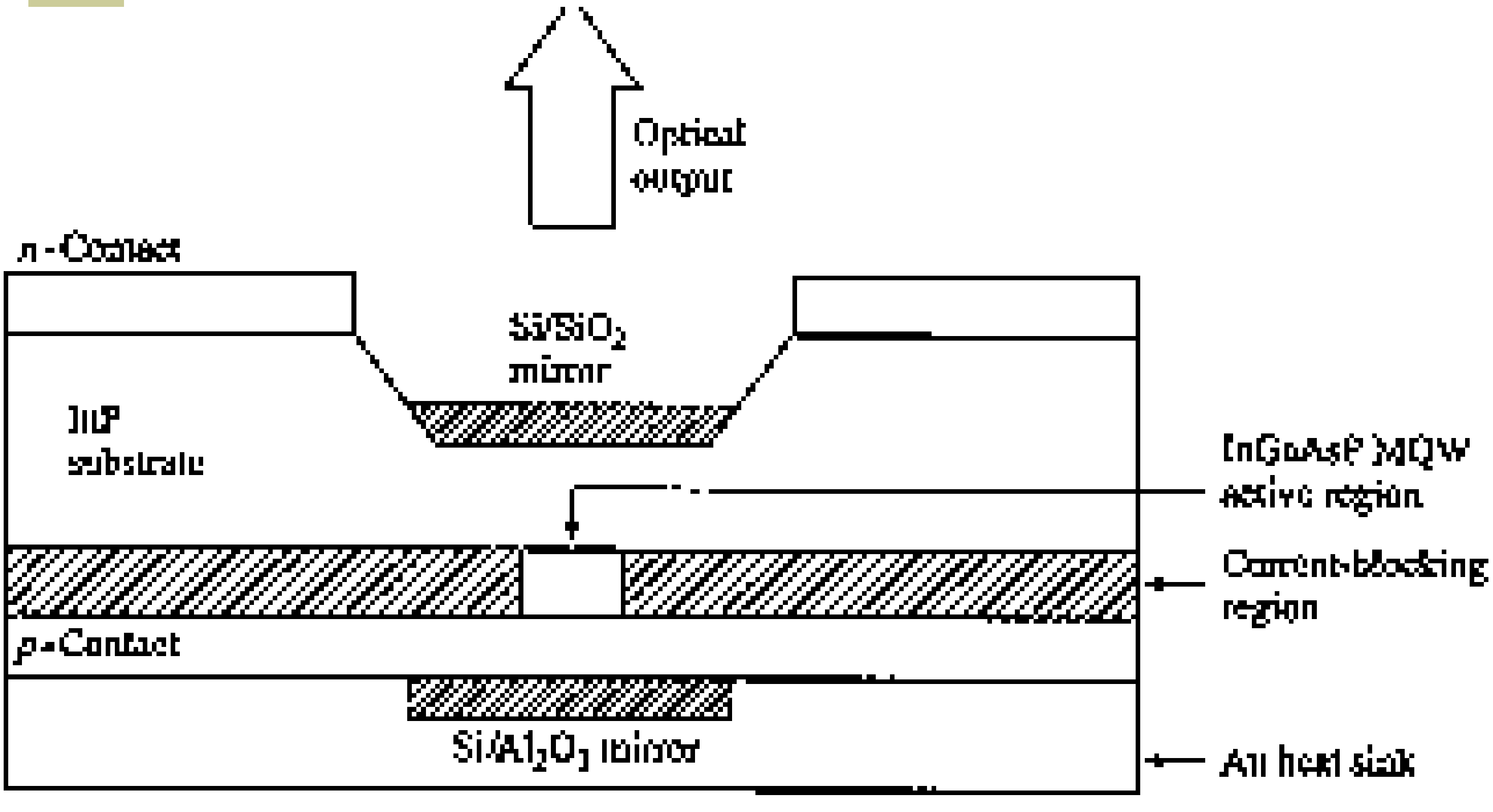
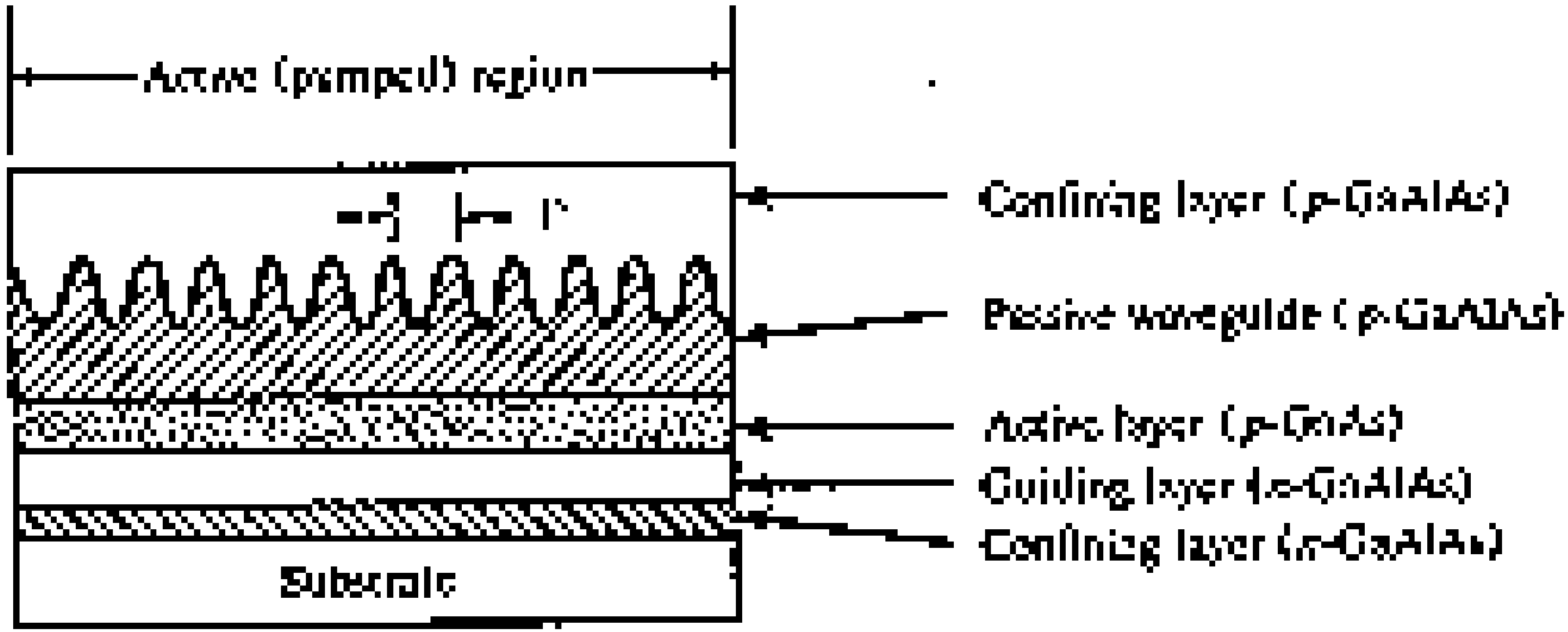


FIGURE 4-27

Basic architecture of a vertical-cavity surface-emitting laser.

Frequency-Selective laser Diodes: Distributed Feedback (DFB) laser

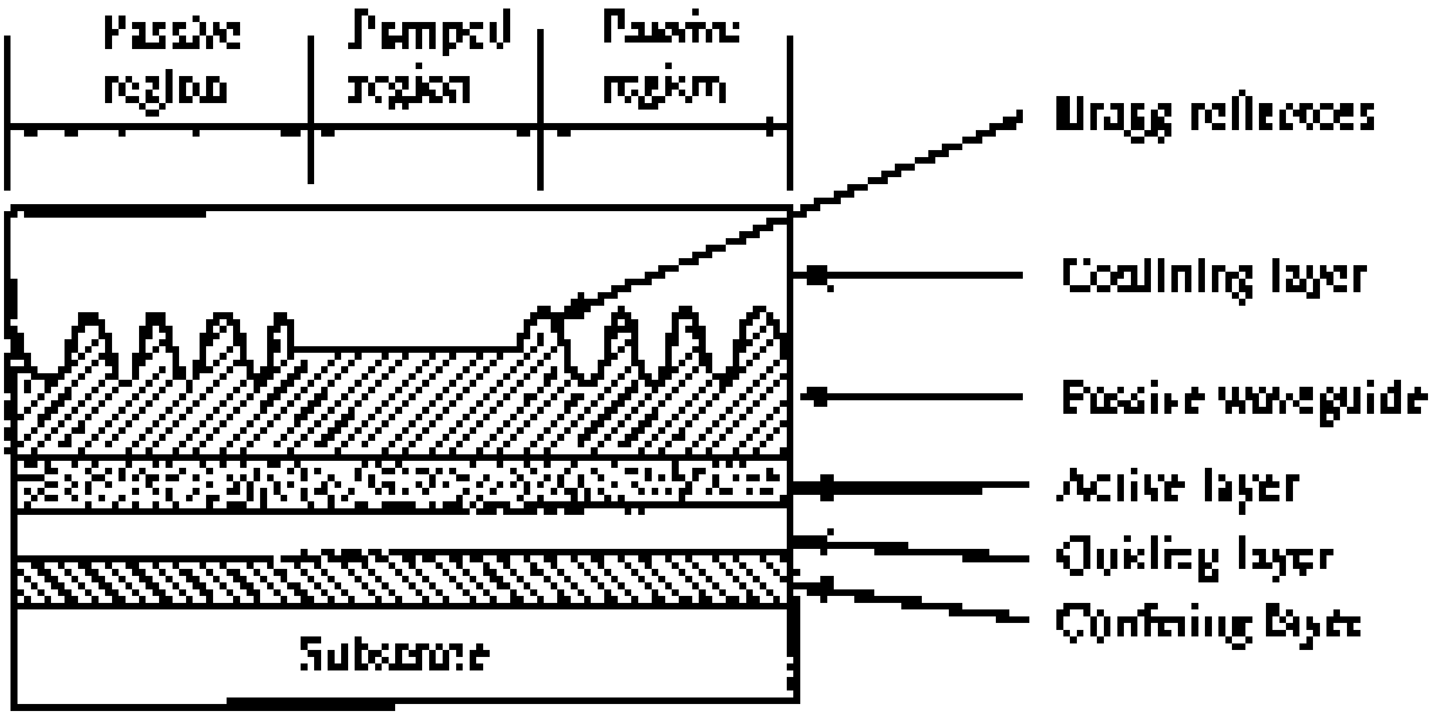
(a)

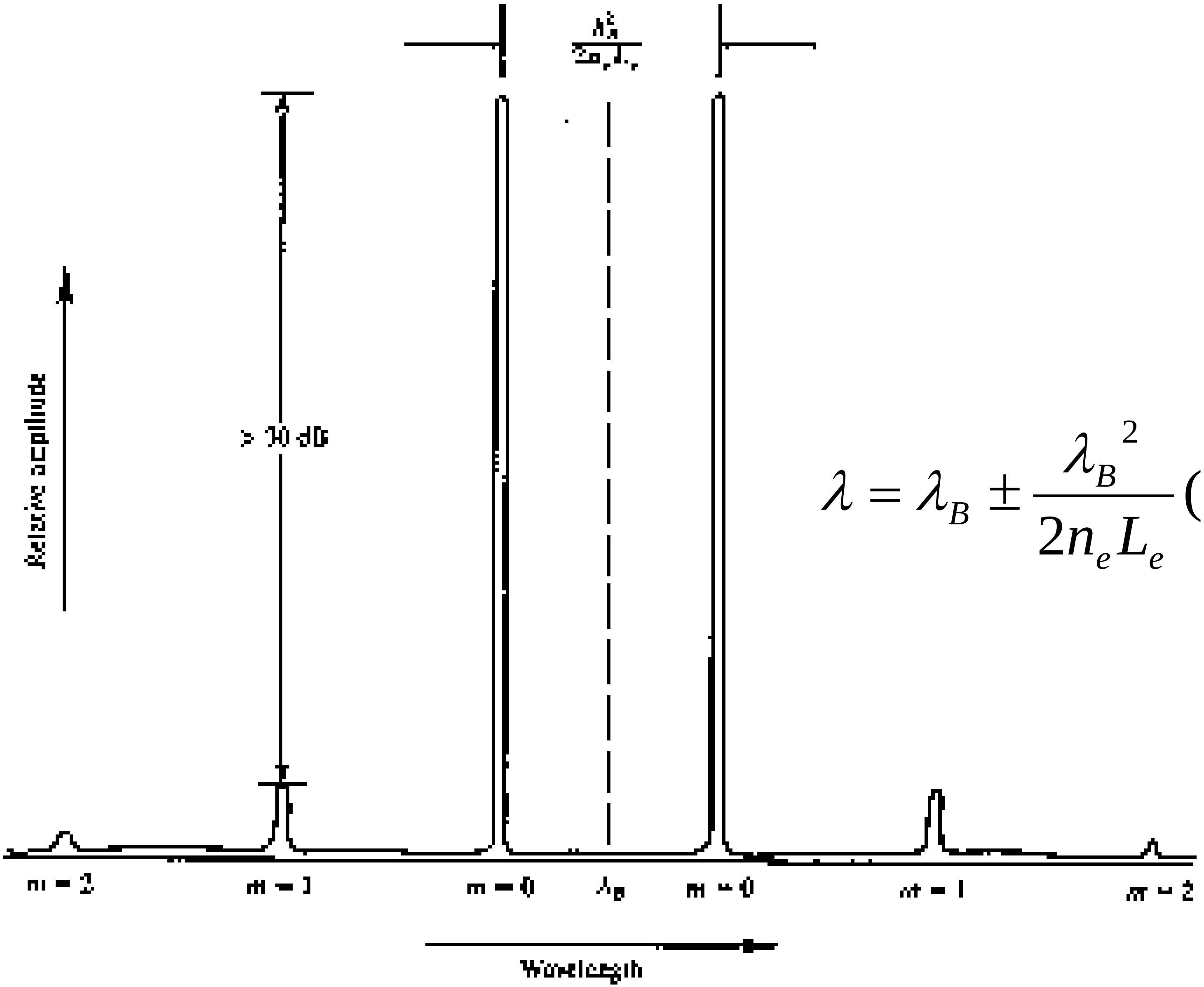


$$\lambda_B = \frac{2 n_e \Lambda}{k}$$ [4-33]

Frequency Selective laser Diodes: Distributed Feedback Reflector (DBR) laser

(a)



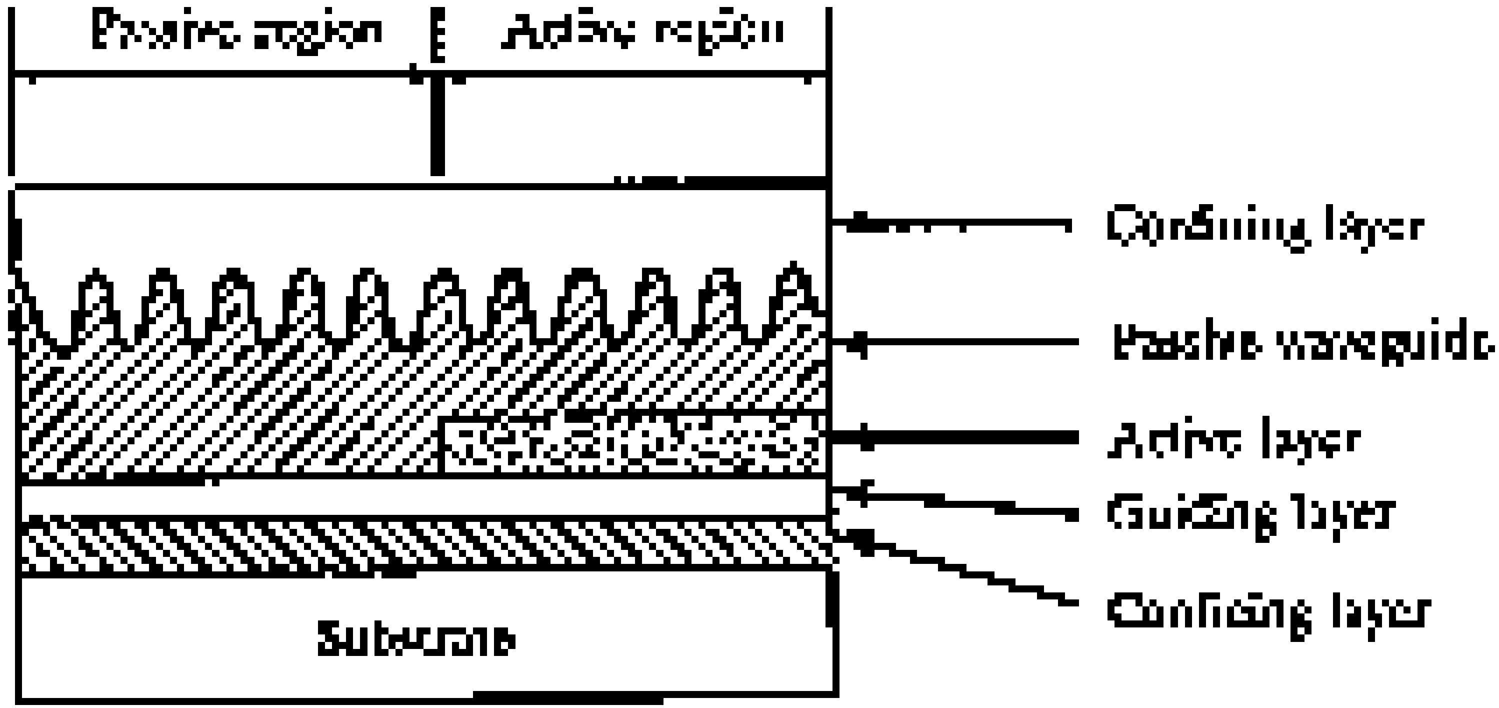


$$\lambda = \lambda_B \pm \frac{\lambda_B{}^2}{2n_e L_e}(m + \frac{1}{2})$$

Output spectrum symmetrically distributed around Bragg wavelength in an idealized DFB laser diode

Frequency-Selective laser Diodes: Distributed Reflector (DR) laser

(c)



Modulation of Optical Sources

- Optical sources can be modulated either directly or externally.
- Direct modulation is done by modulating the driving current according to the message signal (digital or analog)
- In external modulation, the laser emits continuous wave (CW) light and the modulation is done in the fiber

Why Modulation

- A communication link is established by transmission of information reliably
- Optical modulation is embedding the information on the optical carrier for this purpose
- The information can be digital (1,0) or analog (a continuous waveform)
- The bit error rate (BER) is the performance measure in digital systems
- The signal to noise ratio (SNR) is the performance measure in analog systems

Important parameters used to characterize and compare different modulators

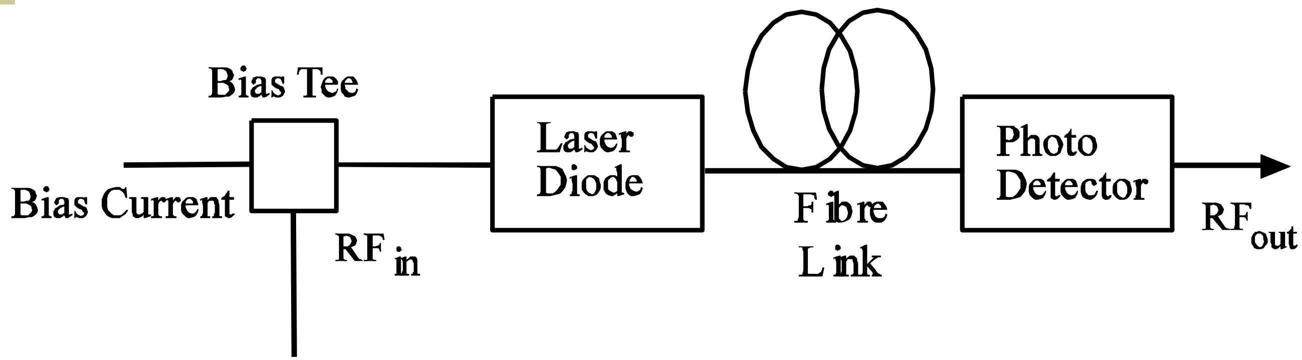
- ***Modulation efficiency*: Defined differently depending on if we modulate intensity, phase or frequency. For intensity it is defined as (Imax – Imin)/Imax.**
- ***Modulation depth*: For intensity modulation it is defined in decibel by 10 log (Imax/Imin).**
- ***Modulation bandwidth*: Defined as the high frequency at which the efficiency has fallen by 3dB.**
- ***Power consumption*: Simply the power consumption per unit bandwidth needed for (intensity) modulation.**

Types of Optical Modulation

- Direct modulation is done by superimposing the modulating (message) signal on the driving current
- External modulation is done after the light is *generated;* the laser is driven by a dc current and the modulation is done after that separately
- Both these schemes can be done with either *digital* or *analog* modulating signals

- Direct modulation of semiconductor lasers
  --- frequency response
  --- relaxation oscillation
  --- chirp
- external modulators:
  --- Electro-absorption modulators
  --- Mach-Zehnder interferometer
- New mechanisms for laser-diode modulation
- Short-pulse techniques

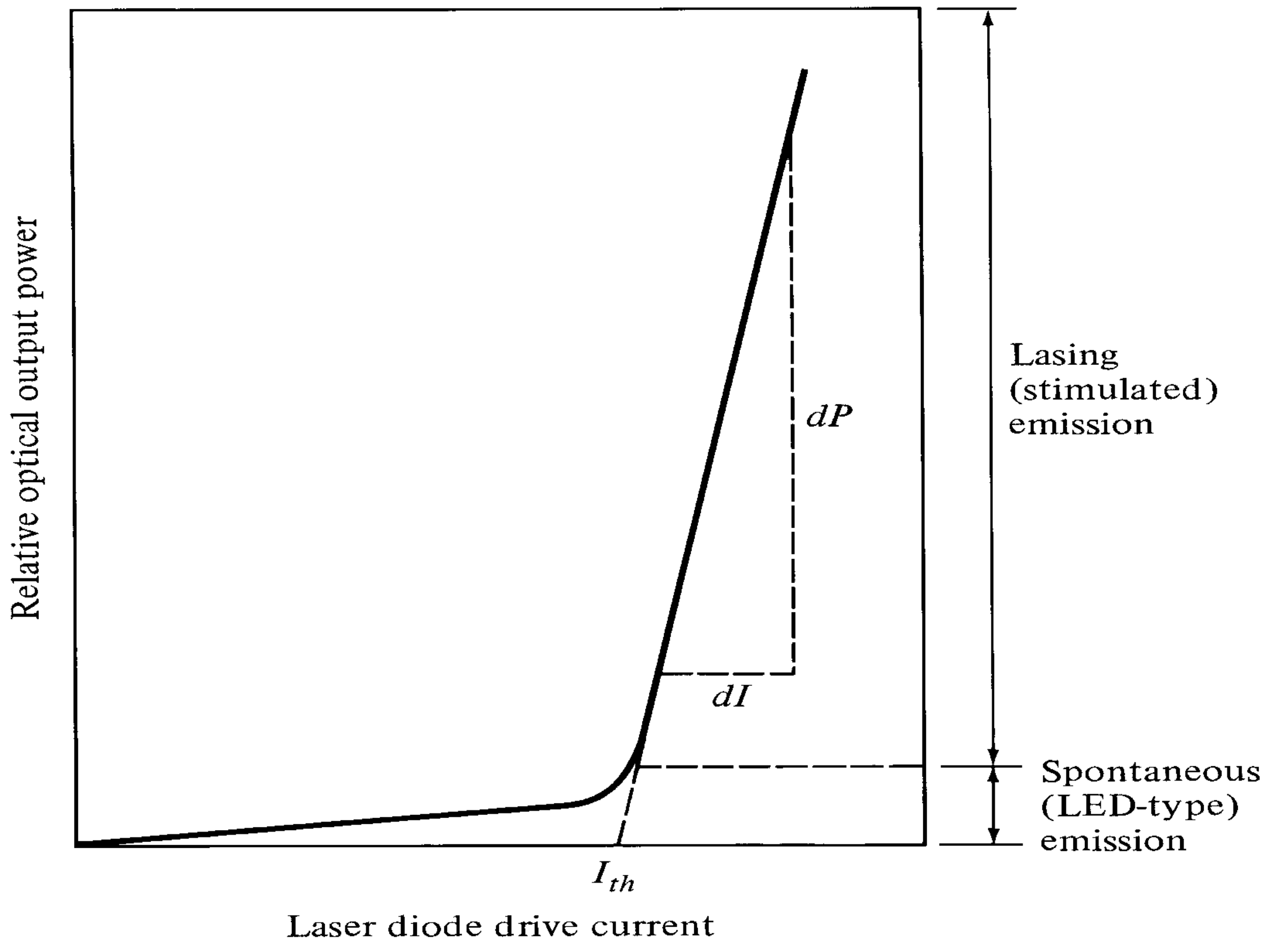
Direct Modulation



- The message signal (ac) is superimposed on the bias current (dc) which modulates the laser
- Robust and simple, hence widely used
- Issues: laser resonance frequency, chirp, turn on delay, clipping and laser nonlinearity

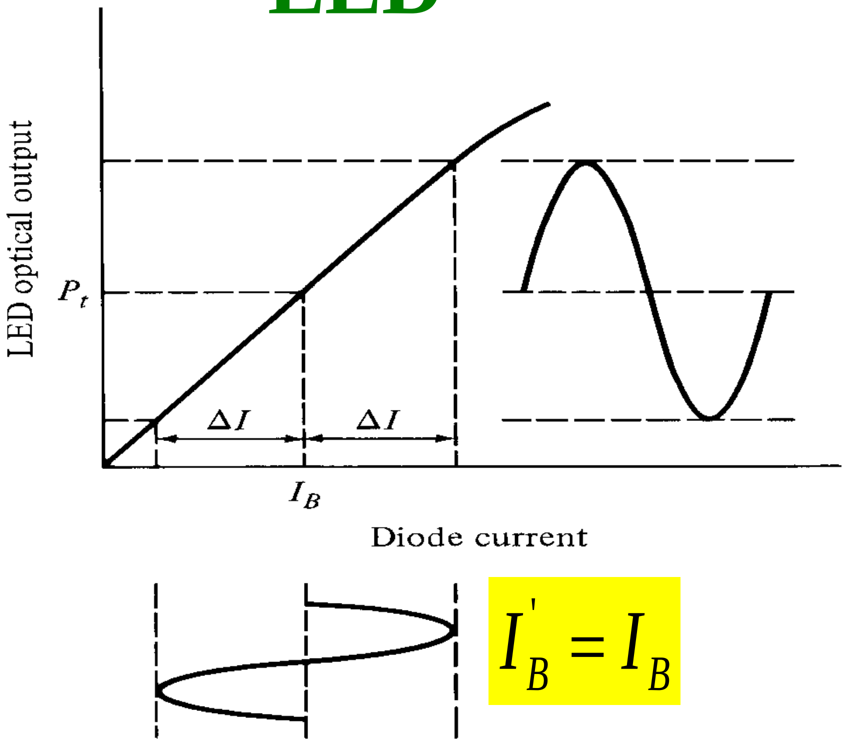
$$\tau_{ph}^{-1} = \frac{c}{n}\left(\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{R_1 R_2}\right) = \frac{c}{n} g_{th}$$

Optical Output vs. Drive Current of a Laser



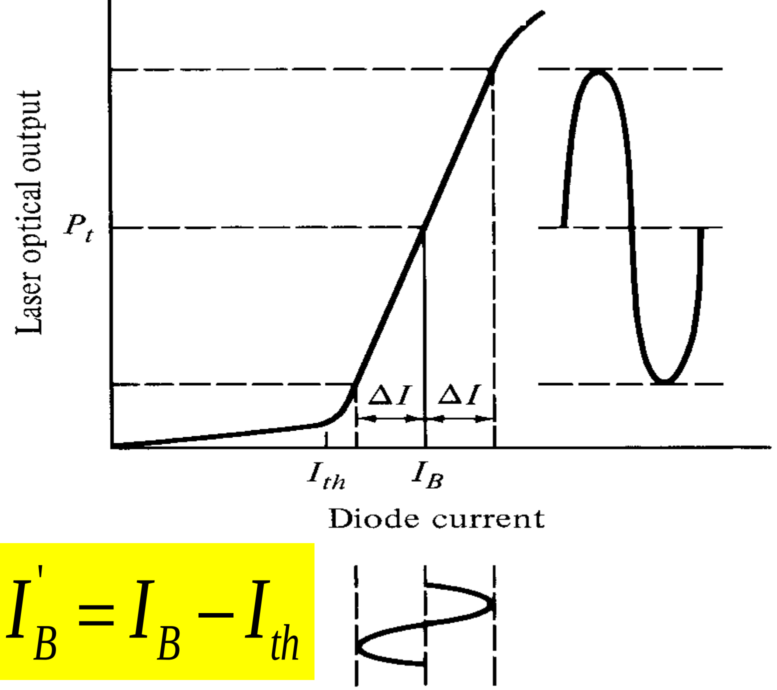
Direct Analog Modulation

LED



$$I_B' = I_B$$

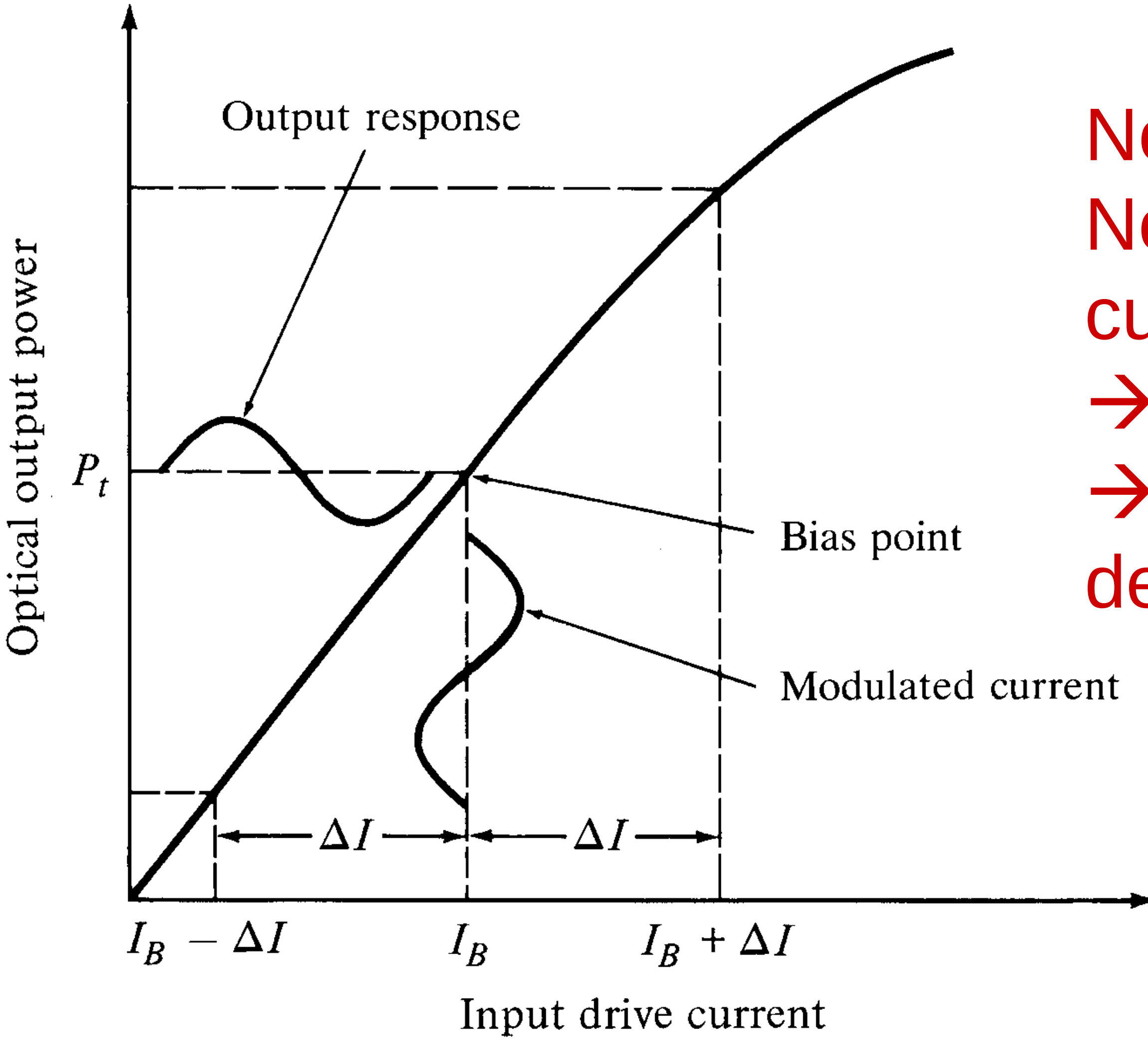
LASER



$$I_B' = I_B - I_{th}$$

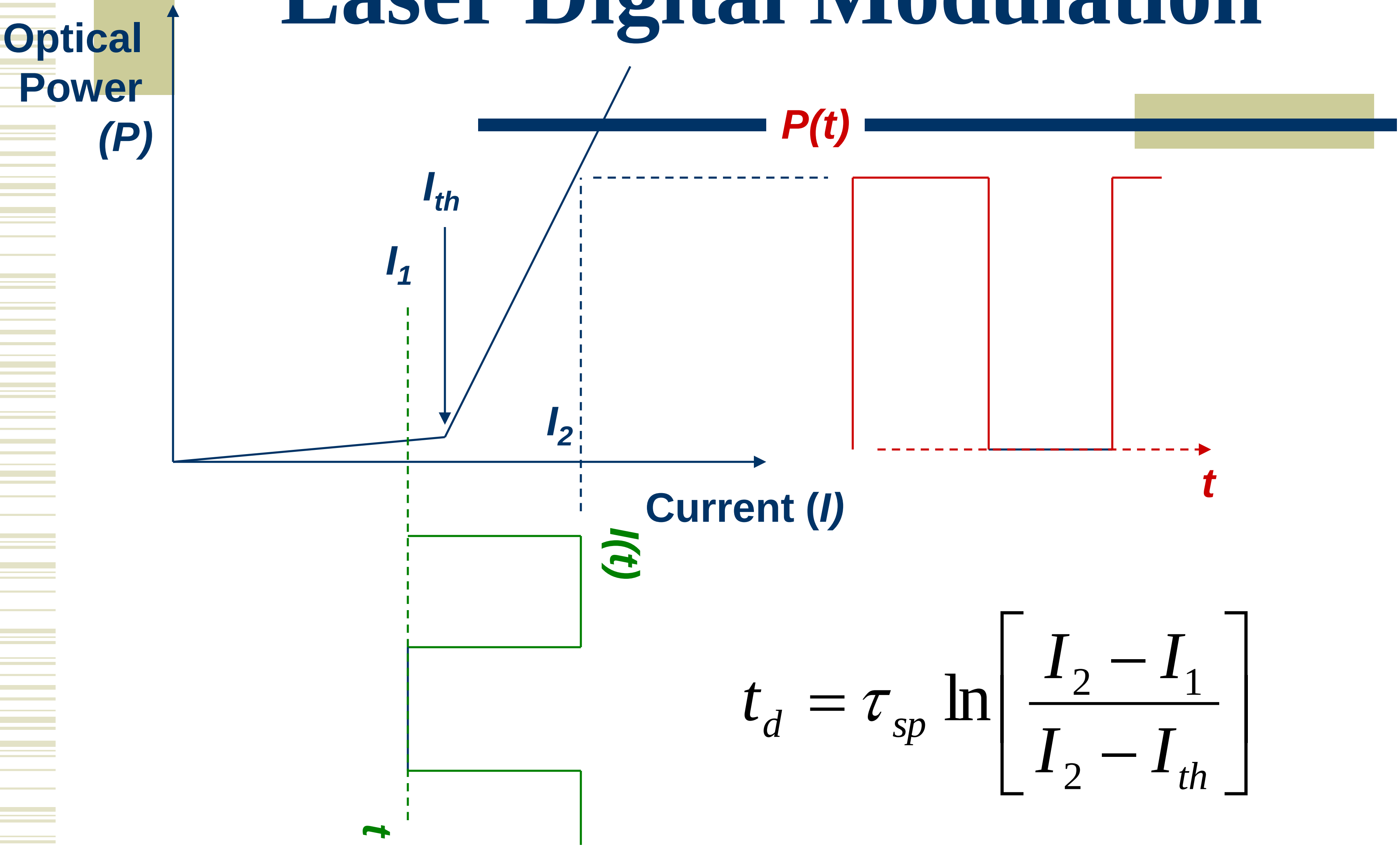
Modulation index (depth) $m = \Delta I / I_B'$

Analog LED Modulation



Note:
No threshold current
→No clipping
→No turn on delay

Laser Digital Modulation



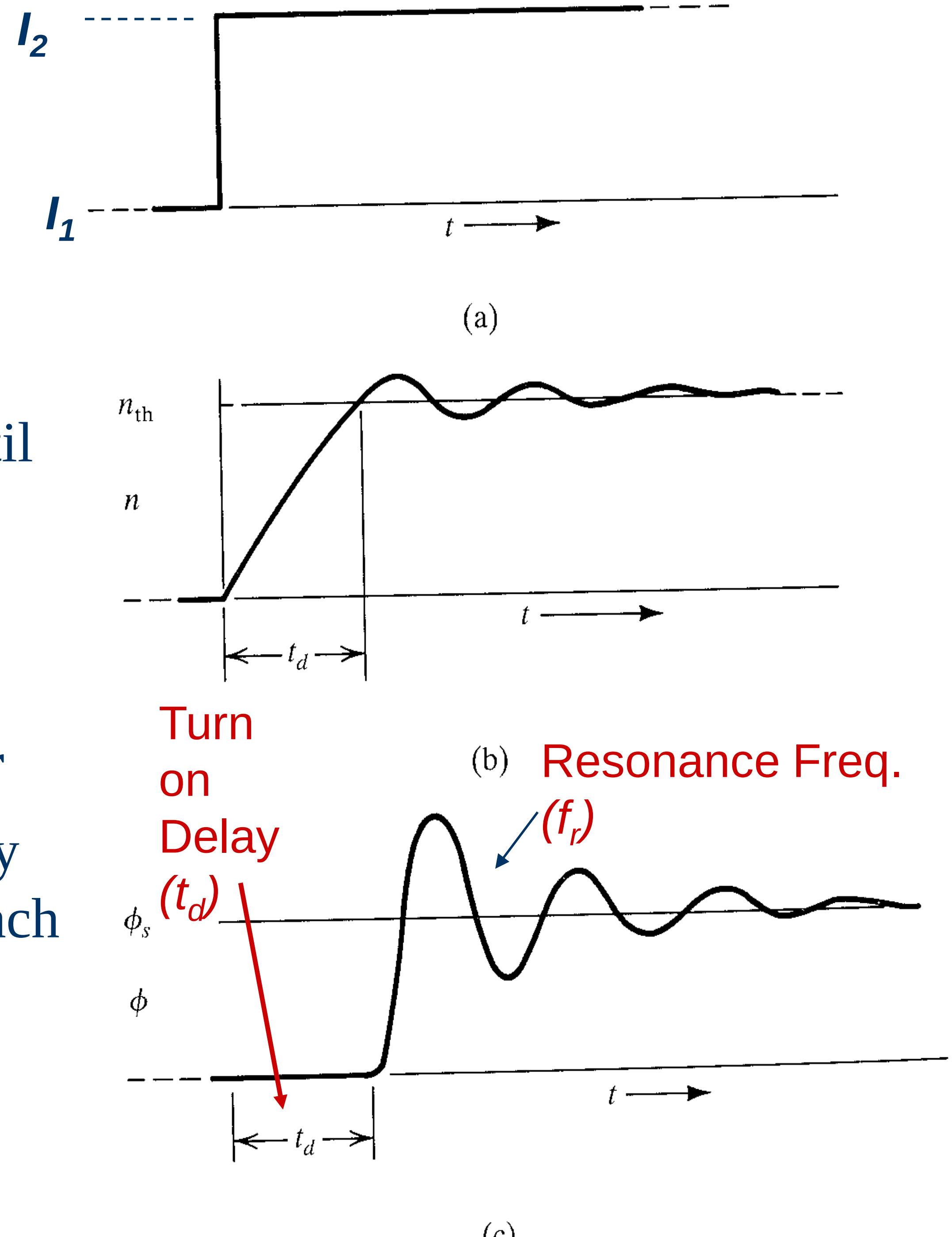
$$t_d = \tau_{sp} \ln\left[\frac{I_2 - I_1}{I_2 - I_{th}}\right]$$

Turn on Delay (lasers)

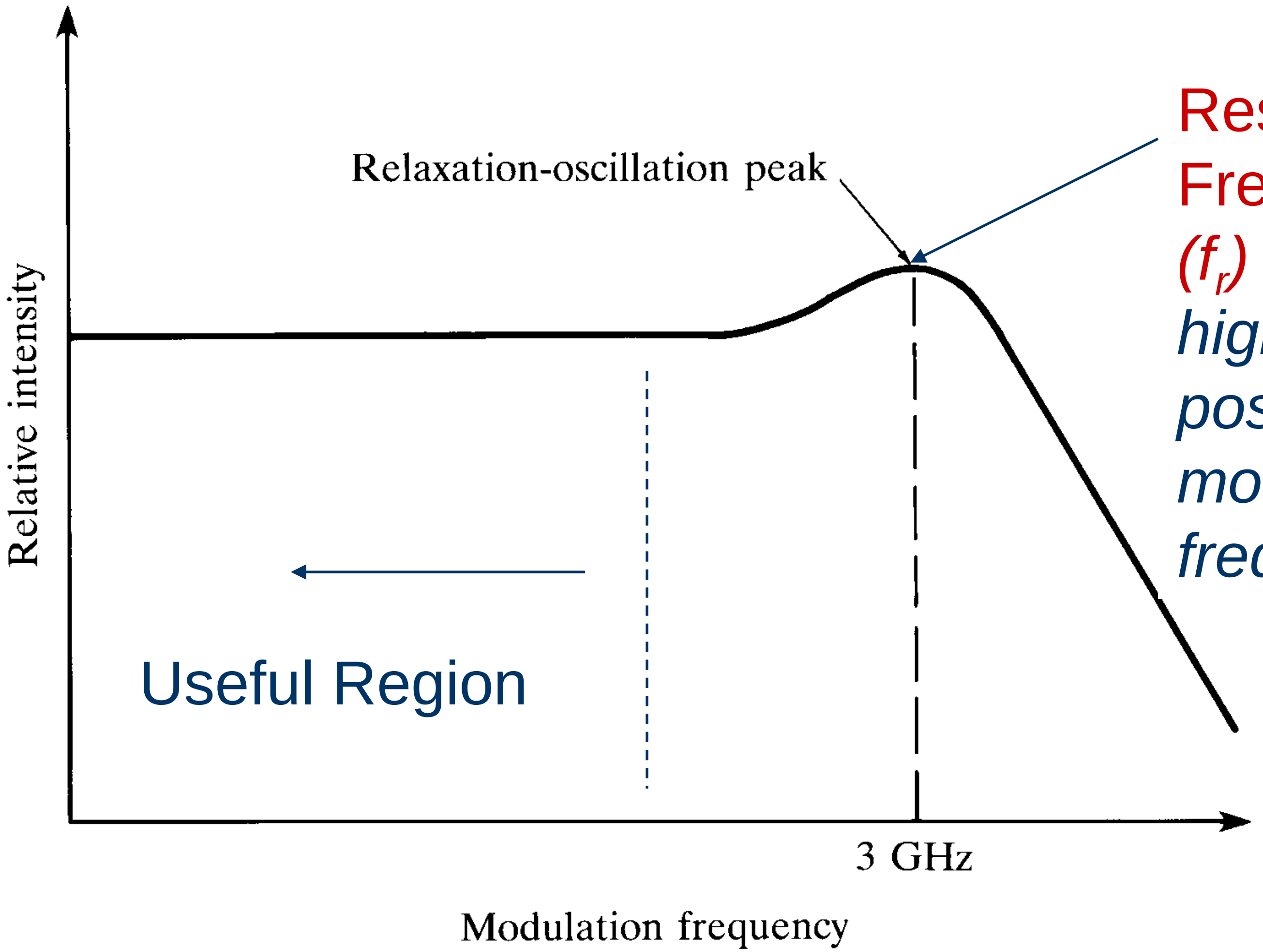
- When the driving current suddenly jumps from low ($I_1 < I_{th}$) to high ($I_2 > I_{th}$) , (step input), there is a finite time before the laser will turn on
- This delay limits bit rate in *digital systems*
- Can you think of any solution?

$$t_d = \tau_{sp} \ln\left[\frac{I_2 - I_1}{I_2 - I_{th}}\right]$$

- Input current
  - Assume step input
- Electron density
  - steadily increases until threshold value is reached
- Output optical power
  - Starts to increase only after the electrons reach the threshold

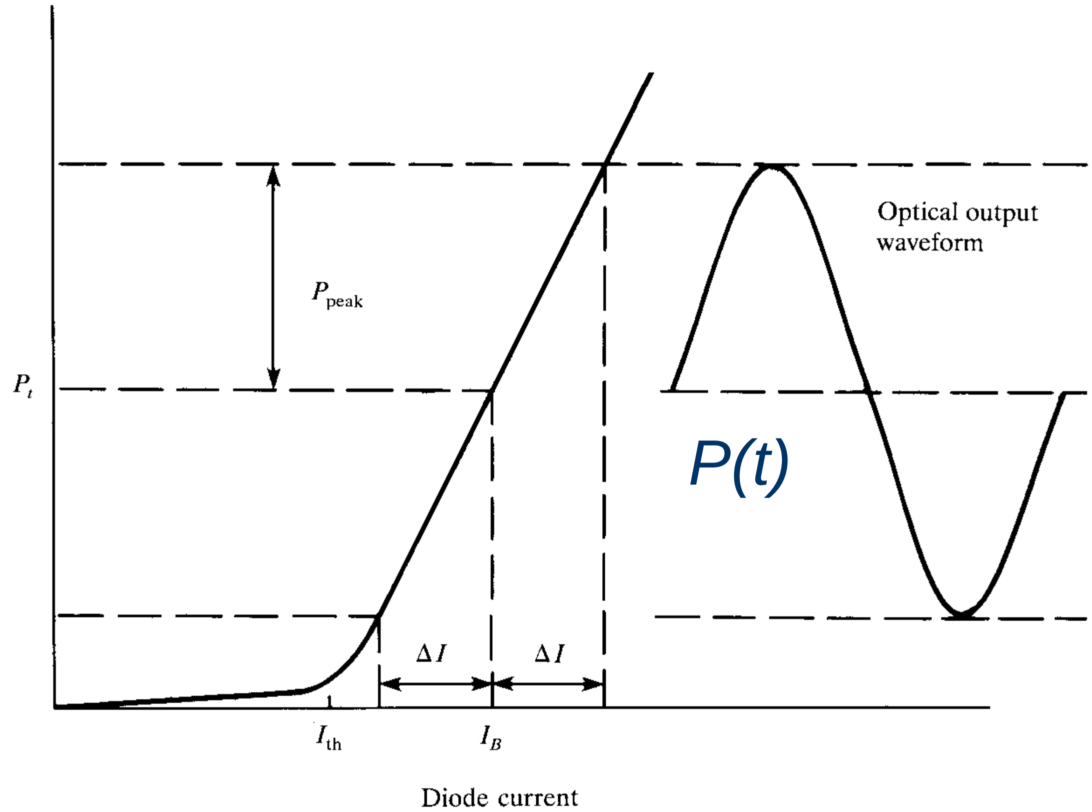


Frequency Response of a Laser

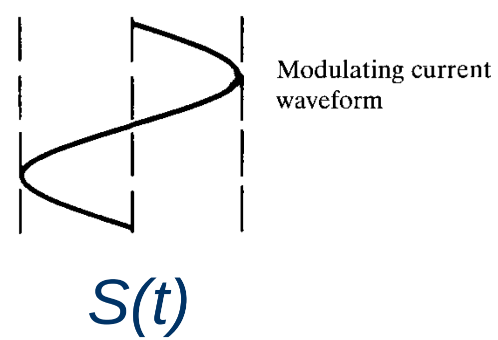


Resonance Frequency *(f_r) limits the highest possible modulation frequency*

Laser Analog Modulation



$$P(t) = P_t[1 + ms(t)]$$

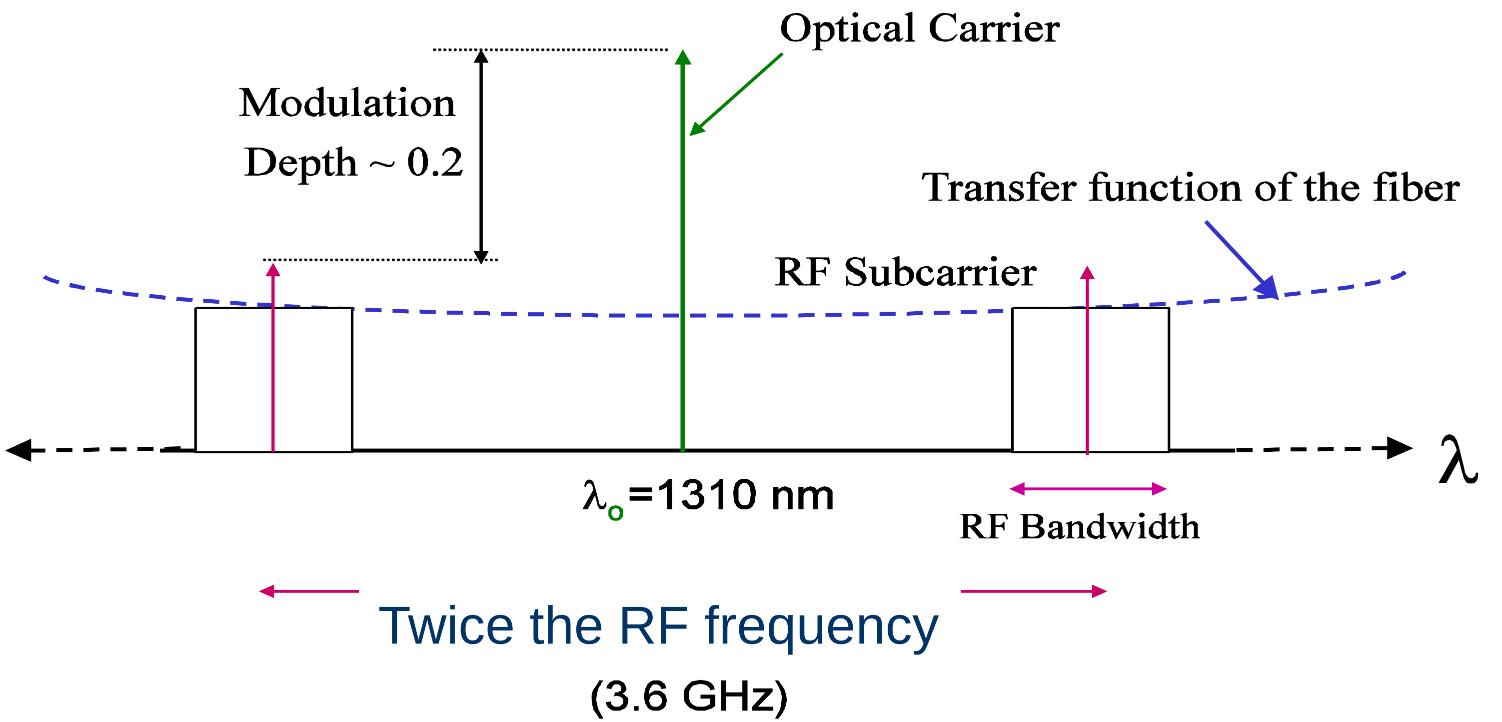


Here *s(t)* is the modulating signal,

P(t): output optical power

P_t: mean value

The modulated spectrum



Two sidebands each separated by modulating frequency

Limitations of Direct Modulation

- Turn on delay and resonance frequency are the two major factors that limit the speed of digital laser modulation
- Saturation and clipping introduces nonlinear distortion with analog modulation (especially in multi carrier systems)
- Nonlinear distortions introduce second and third order intermodulation products
- Chirp: Laser output wavelength drift with modulating current is also another issue

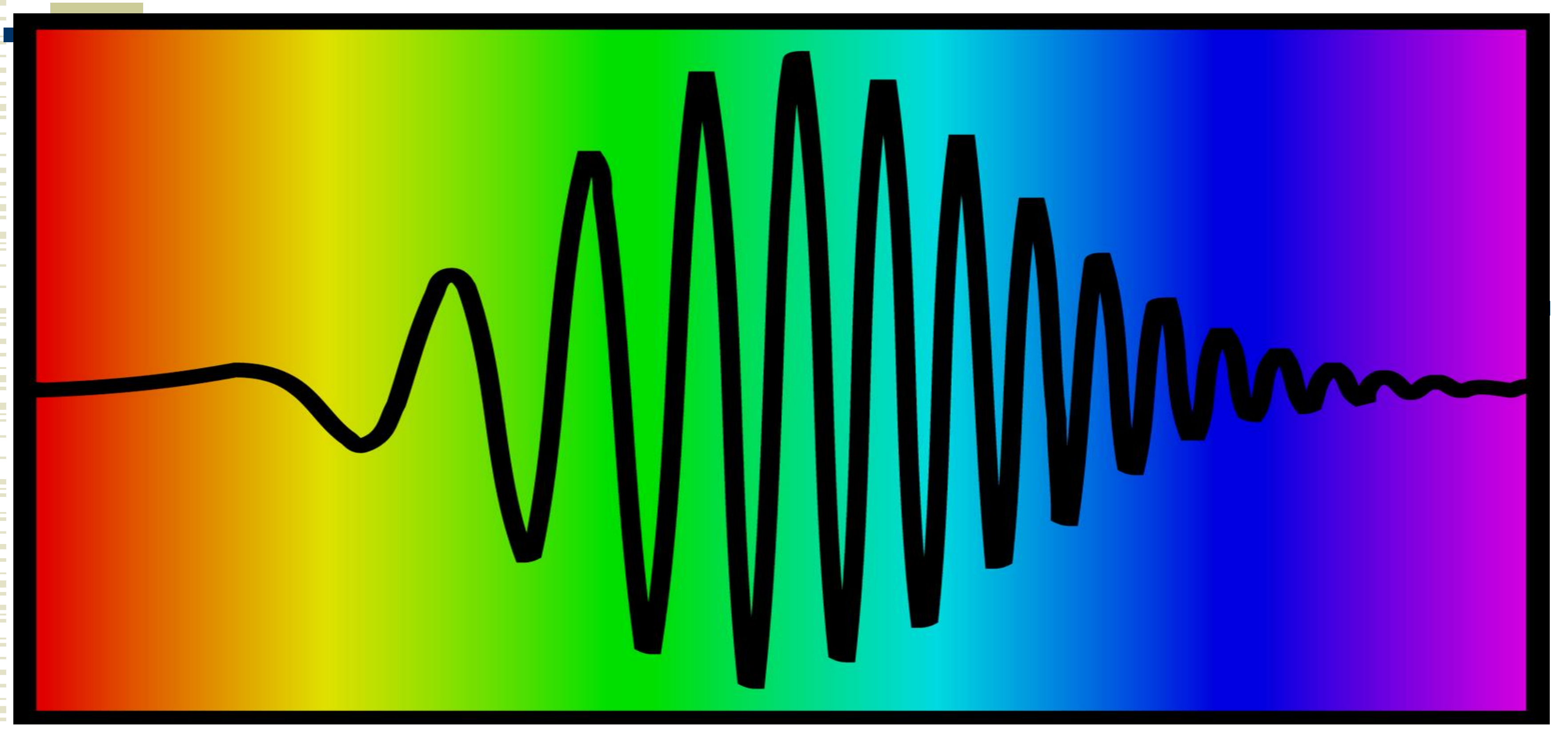
Chirp

In laser diode, the refractive index varies with carrier density.

Modulation → vary current → vary carrier density
→ vary refractive index → index varies with time
→ phase delay varies with time → induces new frequency

frequency varies with time : chirp

- chirp results in broadening of a laser linewidth
- chirp magnitude is ~ 100MHz - GHz/mA,
  ~ 0.001% of center frequency

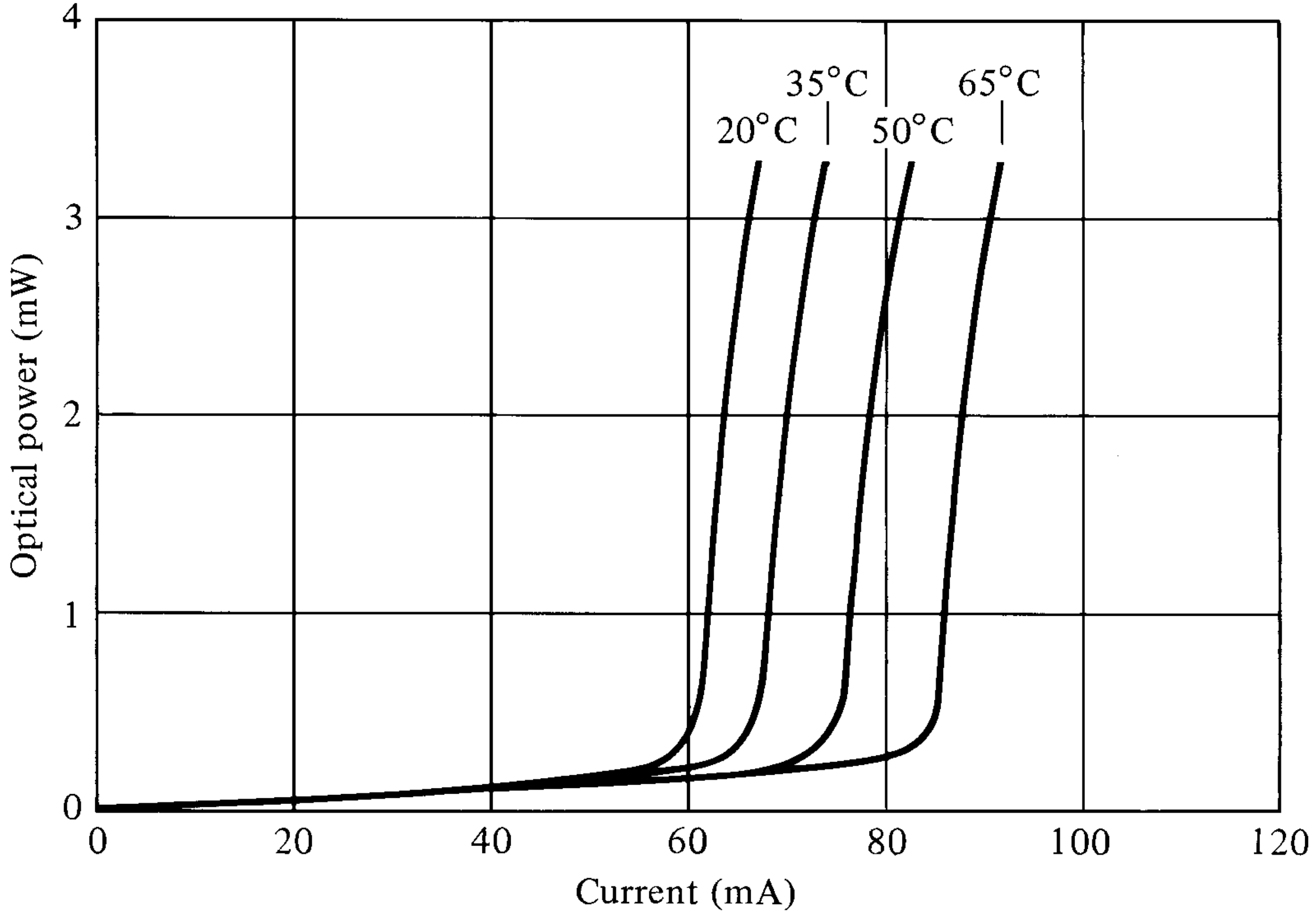


A pulse can have a frequency that varies in time.

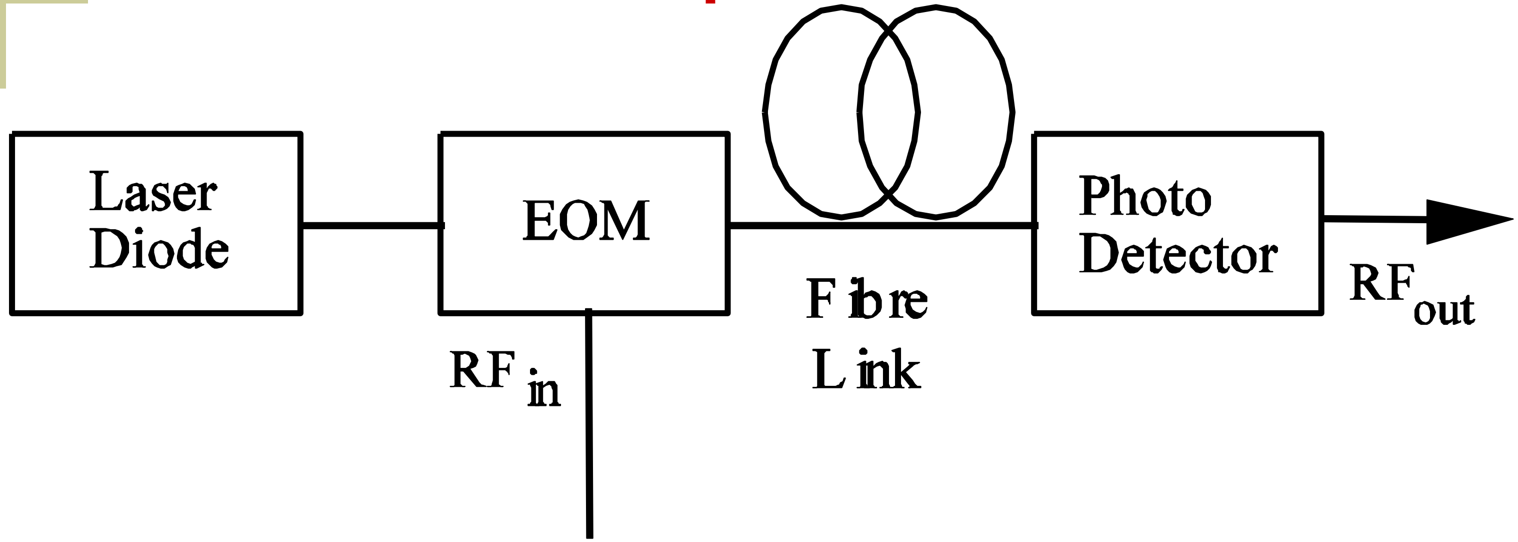
This pulse increases its frequency linearly in time (from red to blue).

In analogy to bird sounds, this pulse is called a "chirped" pulse.

Temperature dependency of the laser is another issue

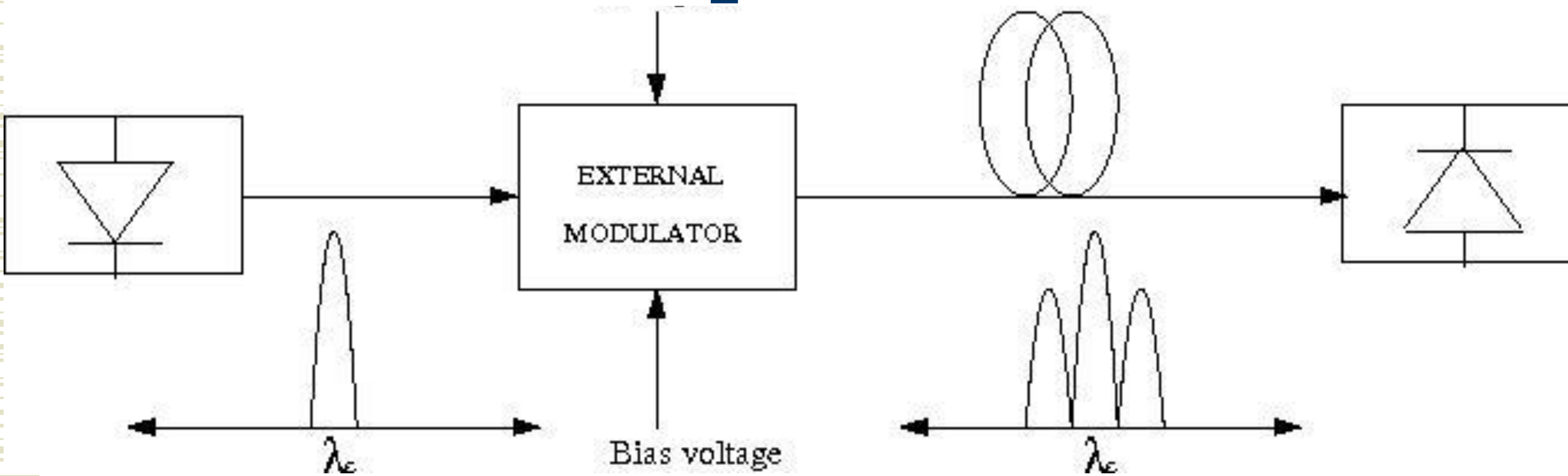


External Optical Modulation



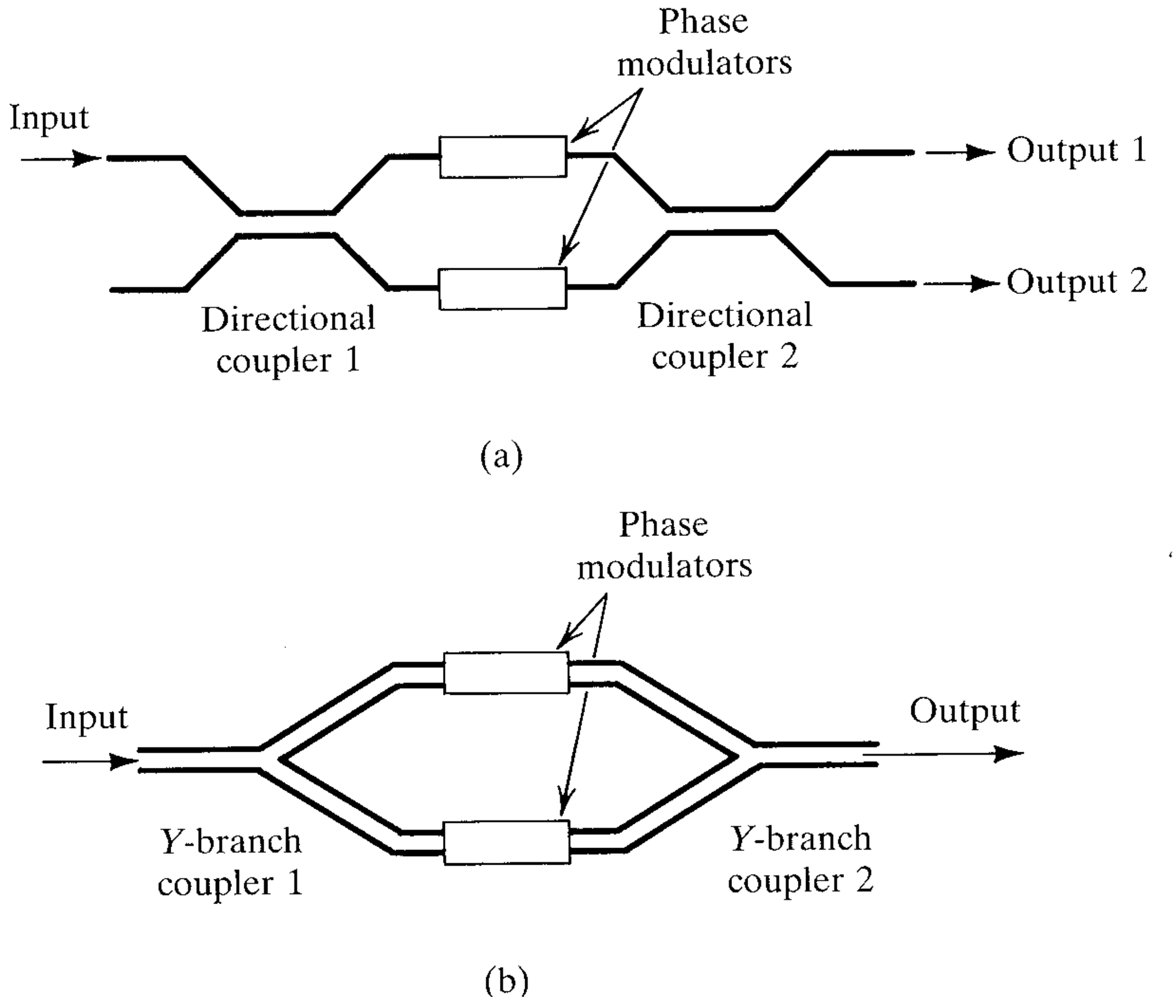
- Modulation and light generation are separated
- Offers much wider bandwidth → up to 60 GHz
- More expensive and complex
- Used in high end systems

External Modulated Spectrum



- Typical spectrum is double side band
- However, single side band is possible which is useful at extreme RF frequencies

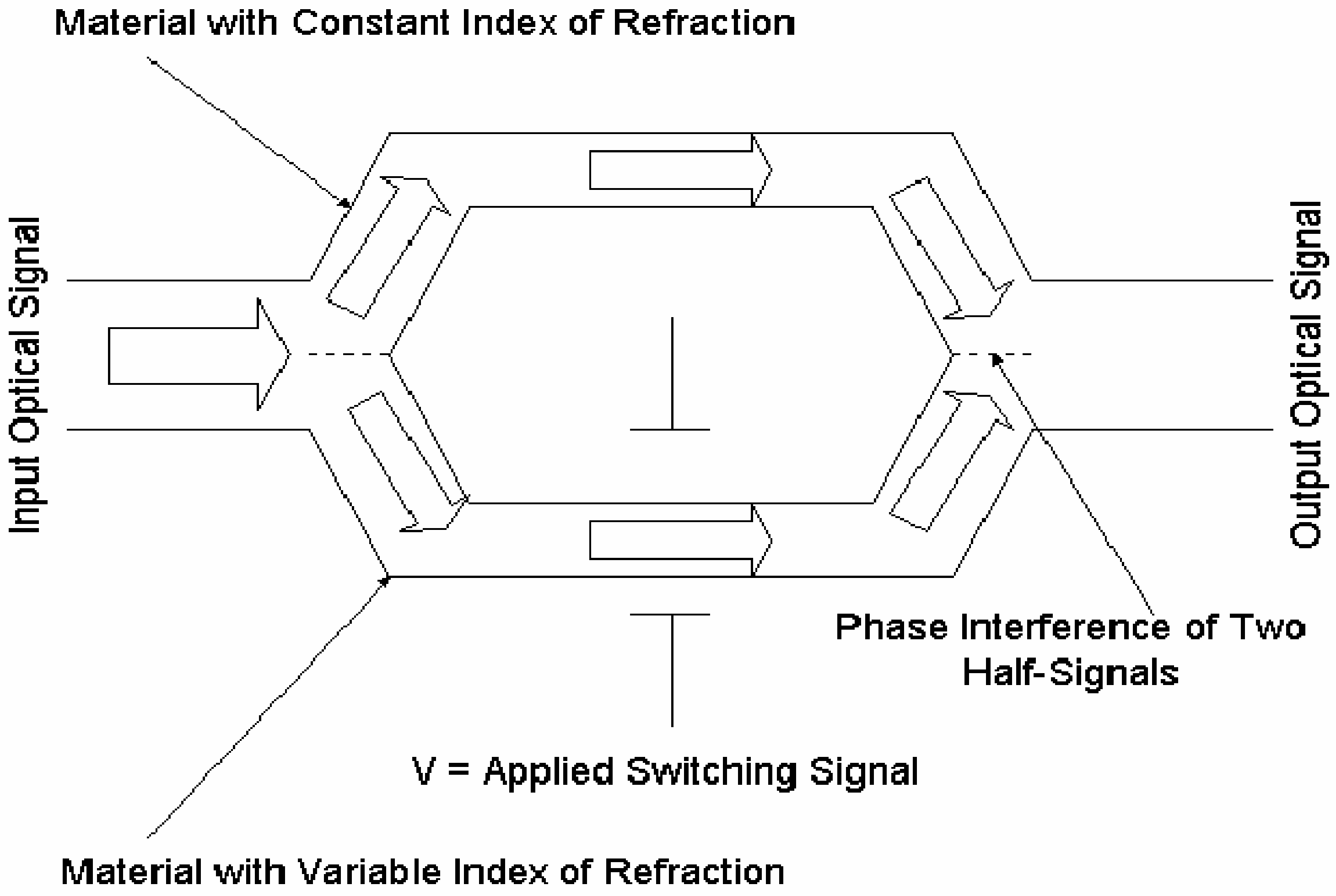
Mach-Zehnder Interferometers



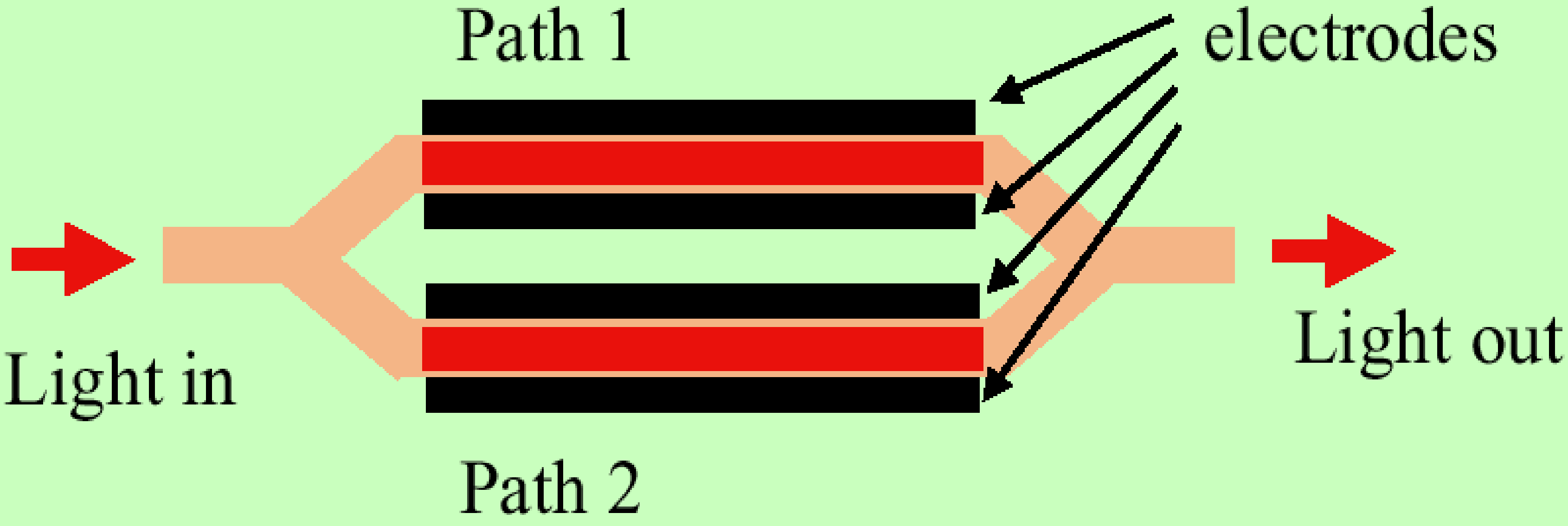
Parameters to characterize performance of optical modulation

- modulation depth
- bandwidth
- insertion loss
- degree of isolation
- power handling
- induced chirp

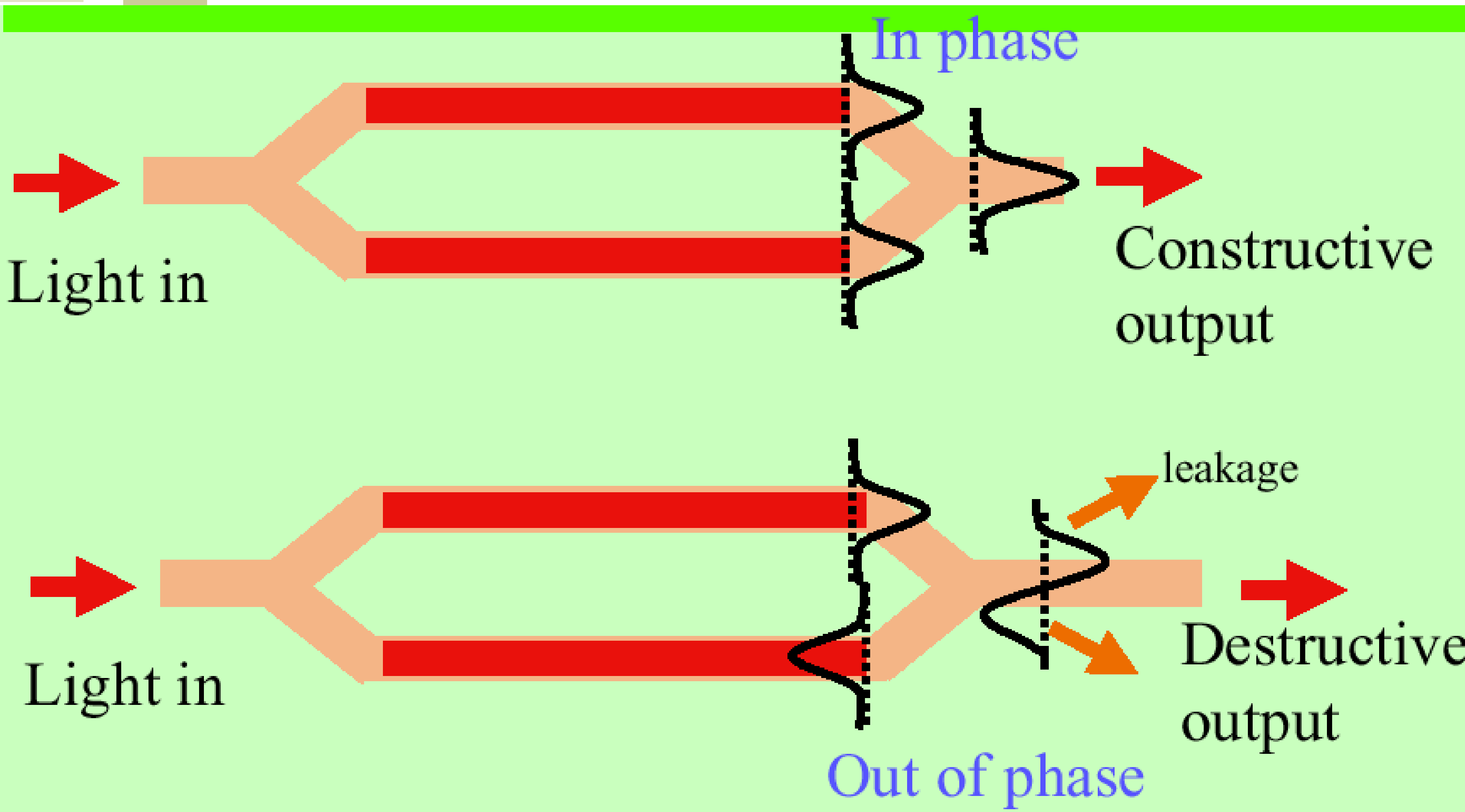
Mach- Zehnder modulator

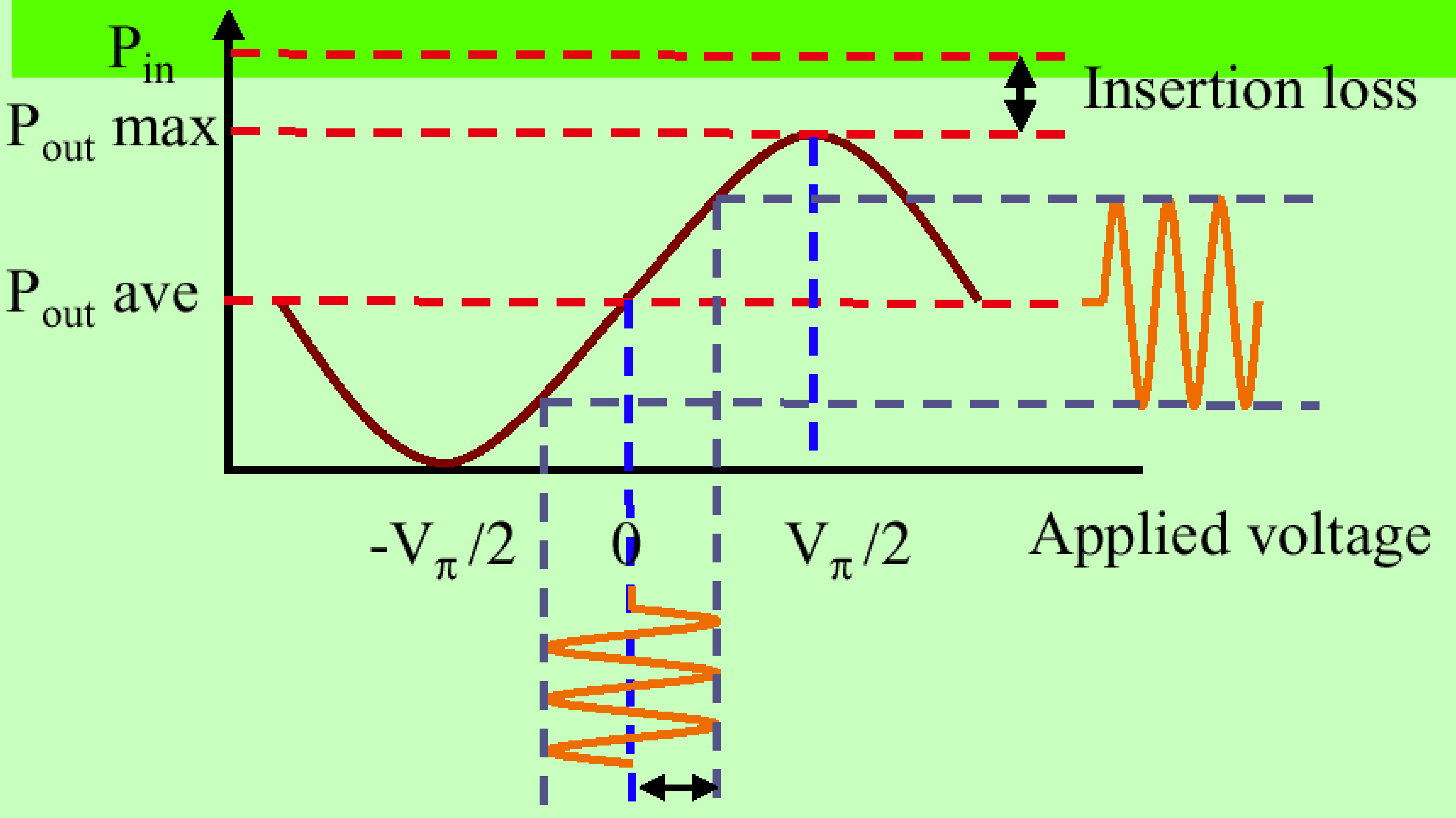


Mach- Zehnder modulator



- Applying voltages to electrodes to change the refractive indices of light paths 1 & 2.
- The optical paths of 1 & 2 vary with the applied voltage.
- In phase → strong output light; out of phase → weak output.
- Output light is then modulated by voltage signal.


In phase
Light in
Constructive output
leakage
Light in
Destructive output
Out of phase

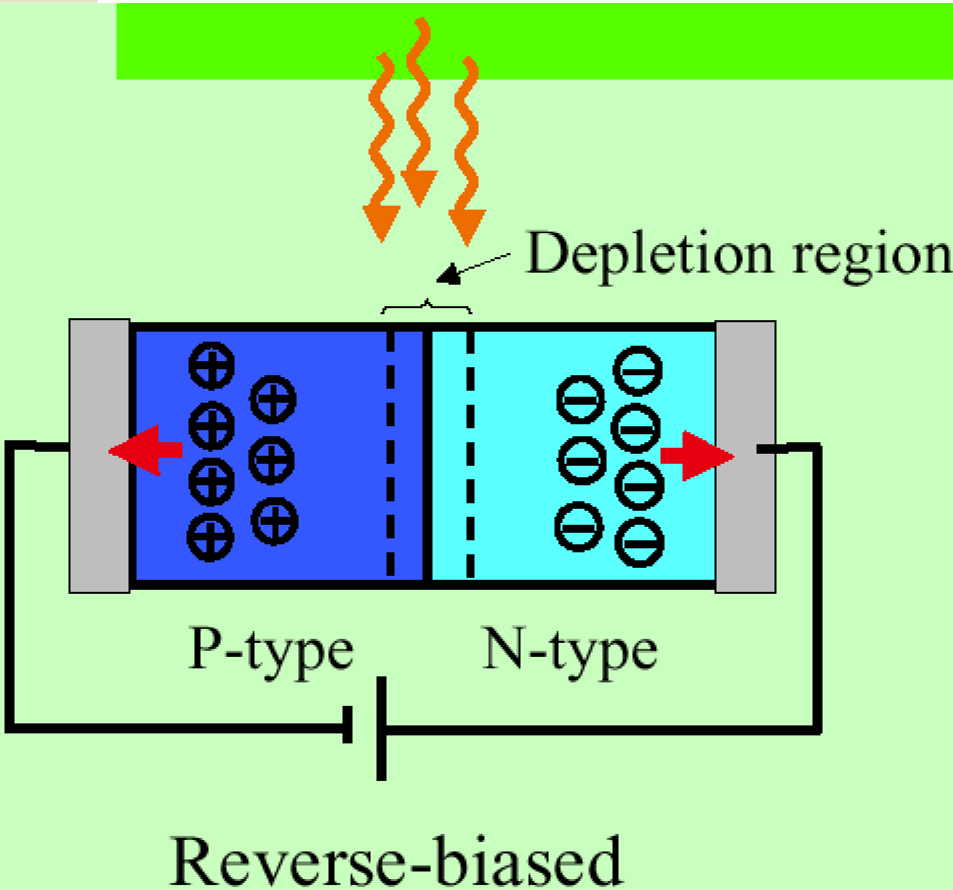


AC modulation

Characteristics of Mach-Zehnder modulator

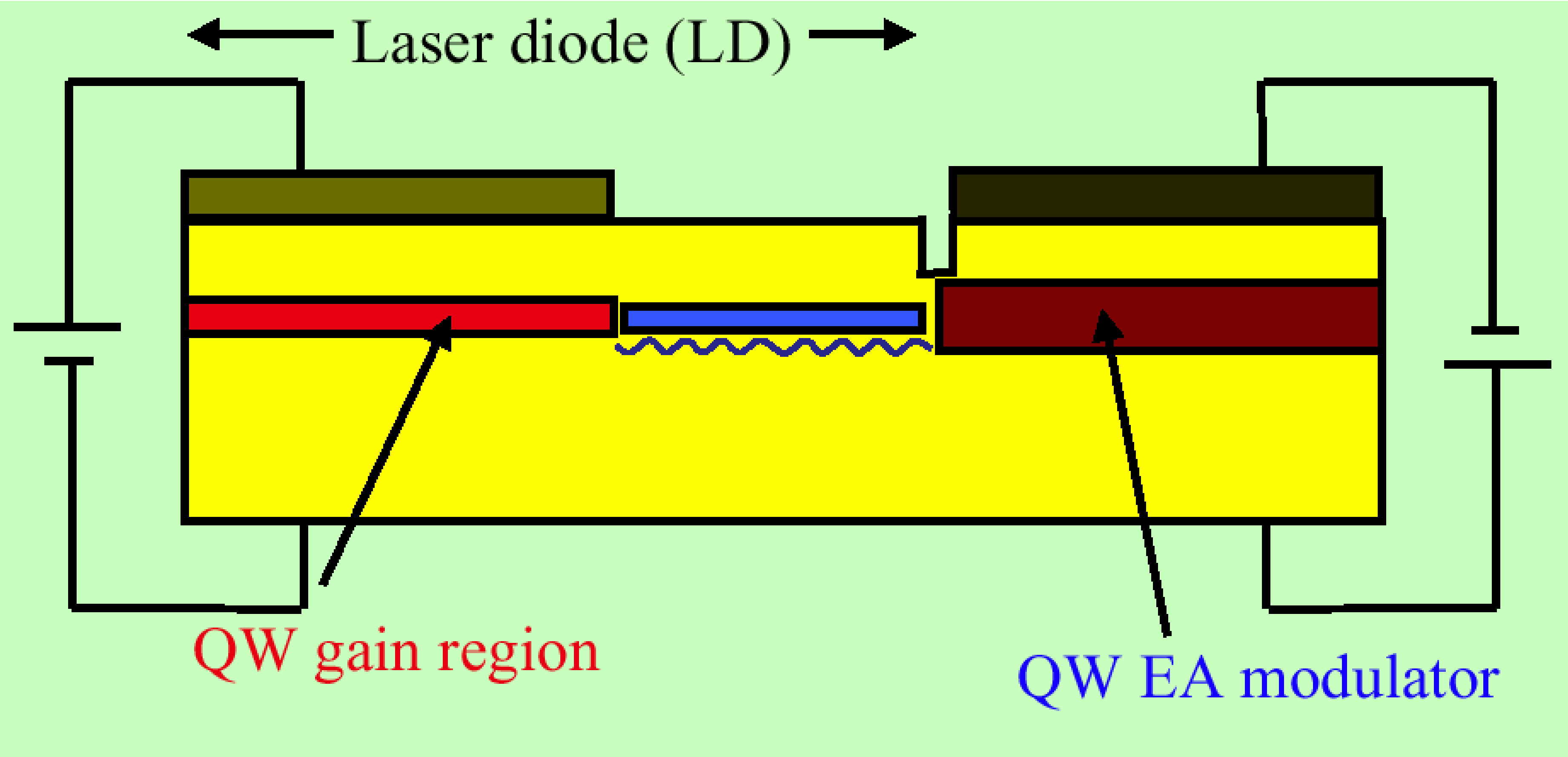
- material: $LiNbO_3$
- modulation depth: better than 20 dB
- bandwidth : could be 60 GHz
- insertion loss : ≥ 4 dB
- power handling : 200 mW
- induced chirp : negligible
- V_π: a few volts, depending on bandwidth

Electro- absorption (EA) modulator



- When the P-N structure in LED is reverse-biased, it becomes light absorption.
- At zero-bias, absorption is weak. Under strong reverse-biased, absorption is strong.
- Light intensity is then modulated by the voltage signal.

Integration of EA modulator with LD



Characteristics of EA modulator

- material: semiconductor QWs
- modulation depth: better than 10 dB
- bandwidth : could be 40 GHz
- insertion loss : almost zero
- power handling : 1 mW
- induced chirp : negligible
- operation voltage: 2 V
- integrable with LD