Optoelectronics
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LED vs. Laser Diode

Typical optical power output vs. forward current for a LED and a laser diode.

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Principles of the Laser Diode

• pn junction in a Degenerate Semiconductor
  - Fermi level in the p region is below $E_v$
  - Fermi level in the n region is above $E_c$
  - With no applied voltage, $E_{fn}=E_{fp}$ yields a very narrow depletion region
  - There is a potential energy barrier, $eV_0$ that prevents n side electrons from diffusing to the p side and vice versa

• When voltage is applied
  - Change in the Fermi level is the work done by the applied voltage, $eV$

• If the junction is forward biased such that $E_{fn} - E_{fp} = eV > E_g$
  - Applied bias diminishes the build in potential barrier
  - Depletion region is no longer depleted
  - There are now more electrons in the conduction band than in the valance band near $E_v$ → Population inversion

The energy band diagram of a degenerately doped p-n with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

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Principles of the Laser Diode

- Population inversion region is a layer along the junction called the inversion layer (active region)
- An incoming photon with energy $E_c - E_v$ cannot excite an electron in $E_v$ to $E_c$ as there are hardly any present in the valance band within the active region
- Hence there is more stimulated emission than absorption
- The optical gain present in the active region due to lack of probability of valance electron absorption

(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T \approx 0$ in the SCL under forward bias such that $E_{Fn} - E_{FP} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy.

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Figure 15.5 An optical beam at $\omega_0$ with intensity $I(\omega_0)$ is incident on a pumped semiconductor medium characterized by quasi-Fermi levels $E_{Fc}$ and $E_F$. A single level pair $a \rightarrow b$ with the same $k$ value is shown. The induced transition $a \rightarrow b$ contributes one photon to the beam.
Electro-optical Performance of III/V Diodes

- **injection pumping**: Optical pumping is achieved by forward diode current and the pumping energy is an external battery.
- For laser we also need an optical resonator cavity. This is achieved through the use of a slab waveguide with a high index contrast at the emission end.
- Wavelength of the radiation that can build up in the cavity depends on the length \( L \) in half multiples:

\[
m \frac{\lambda}{2n} = L
\]

A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

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- 2 critical current identifiers
- Transparency current: Current above which no net photon absorption occurs
- Threshold current: current above which optical gain overcomes all photon losses in the cavity

Typical output optical power vs. diode current \( I \) characteristics and the corresponding output spectrum of a laser diode.

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Heterojunction Laser Diodes

- Main issue with homojunction diodes is that the laser threshold current density is too high for practical uses.
  - Ex. $J_{th} = 500\text{A/mm}^2$ for GaAs at 300K
- Heterostructured diodes reduce these current densities by orders of magnitude
- This is achieved through a combination of carrier confinement (mismatched materials), and photon confinement (geometric shape of the waveguide)
- Double heterojunction (DH) devices with npp layers allow for designed confinement of the active region
- Lower refractive index of the AlGaAs enhances the mode confinement in comparison to a homo or simple heterojunction device
- Significantly reduces threshold current density

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Edge Emitting Lasers

- Very similar to ELED devices presented in chapter 3
- Additional contacting layer of p-GaAs next to the p=AlGaAs provides better contacting and avoids Schottky junction which would limit the current in the device.
- p- and n- AlGaAs layers provide carrier and optical confinement in the vertical direction
- Laser emission in the active p-GaAs(or a different AlGaAs constitution) region is between 870-900 nm depending on doping.
- AlGaAs and GaAs have negligible lattice mismatch yielding very few defects in the crystal that would lead to excessive threshold currents
- Also, the stripe electrode across the top confines the electric field and thus the optically active region providing additional geometrical confinement
- Such lasers are called gain guided, b/c the current density generated is guided by the electric field between the stripe electrode and the bottom electrode

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Figure 15.10 A typical double heterostructure GaAs/GaAlAs laser. Electrons and holes are injected into the active GaAs layer from the $n$ and $p$ GaAlAs. Photons with frequencies near $\nu = E_g/h$ are amplified by stimulating electron–hole recombination.
Figure 15.12  The magnitude of the energy gap in Ga$_{1-x}$Al$_x$As as a function of the molar fraction $x$. For $x > 0.37$ the bandgap is indirect. (After Reference [11].)
Figure 15.15 III–V compounds: lattice constants versus energy bandgaps and corresponding wavelengths. The solid lines correspond to direct-gap materials and the dashed lines to in-direct-gap materials. The binary-compound substrates that can be used for lattice-matched growth are indicated on the right. (After Reference [11].)
Buried Heterostructure LDs

- Although the stripe electrode geometry provides some geometric confinement, it is more advantageous to restrict lateral geometry physically through the use of confining layers along the side of the diode.
- Creation of a optical waveguide in both vertical and horizontal directions aids in reducing optical cavity modes and promotes confinement.
- Significantly reduces current density required for stimulated emission.
Example: Modes in a laser and the Optical Cavity length

- AlGaAs heterojunction LD with cavity length of 200 um and radiation peak of 870 nm.
- What is the mode integer of the peak radiation and the separation between modes in the cavity.
- If the optical gain vs wavelength characteristics has a FWHM wavelength of 6nm, how many modes are there within this bandwidth?
- How many modes are there if the cavity has a length of 20 um?

\[ m \frac{\lambda}{2n} = L \]

\[ m = \frac{2nL}{\lambda} = \frac{2(3.7)(200 \times 10^{-6})}{(900 \times 10^{-9})} = 1644 \]

\[ \delta \lambda_m = \frac{2nL}{m} - \frac{2nL}{m+1} \approx \frac{2nL}{m^2} = \frac{\lambda^2}{2nL} \]

\[ L = 200 \times 10^{-6} m \]

\[ \delta \lambda_m = \frac{(900 \times 10^{-9})^2}{2(3.7)(200 \times 10^{-6})} = 0.547nm \]

\[ \Delta \lambda_{1/2} = 6nm \]

\[ \Delta \lambda_m = \frac{0.547nm}{10mod es} \]

Number of laser modes depends on how the cavity modes intersect the optical gain curve. In this case we are looking at modes within the linewidth \( \Delta \lambda_{1/2} \).

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Modes = \( \frac{\text{Linewidth of spectrum}}{\text{Separation of two modes}} \approx \frac{\Delta \lambda_{1/2}}{\Delta \lambda_m} = m \)

\[ L = 20 \times 10^{-6} m \]

\[ \delta \lambda_m = \frac{(900 \times 10^{-9})^2}{2(3.7)(20 \times 10^{-6})} = 5.47nm \]

\[ \frac{\Delta \lambda_{1/2}}{\Delta \lambda_m} = 1.1 \]

1 mode corresponding to 900 nm. In fact, \( m \) must be an integer and when \( m = 1644 \) and \( \text{lamda} = 902/4 \) nm. It is apparent that reducing the cavity suppress higher order modes.
Elementary Laser Diode (LD) Characteristics

- Longitudinal mode: length determined
- Lateral mode: width determined
- Emission is either multimode or single mode depending on the optical resonating structure and the pumping current level

The laser cavity definitions and the output laser beam characteristics.

Output spectra of lasing emission from an index guided LD. At sufficiently high diode currents corresponding to high optical power, the operation becomes single mode. (Note: Relative power scale applies to each spectrum individually and not between spectra)
Laser Performance as a Function of Temperature

- Output spectrum and mode properties are temperature dependent.
- Single mode LDs exhibit a mode hop at certain temperatures corresponding to a change in peak emission wavelength.
- Nominal wavelength of the laser increases slowly between hops due to change in refractive index, n, with temperature.
- Slope efficiency determines laser efficiency and is not the same as LED conversion efficiency stated in chapter 3.

\[ \eta_{\text{slope}} = \frac{P_o}{I - I_{\text{th}}} \]

Output optical power vs. diode current as three different temperatures. The threshold current shifts to higher temperatures.

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Peak wavelength vs. case temperature characteristics. (a) Mode hops in the output spectrum of a single mode LD. (b) Restricted mode hops and none over the temperature range of interest (20 - 40°C). (c) Output spectrum from a multimode LD.

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Example: Laser Output Wavelength Variations

• Given: Refractive index, n, of GaAs has a temp dependence \( \frac{dn}{dT} \approx 1.5 \times 10^{-4} K^{-1} \)
• Estimate the change in emitted wavelength from 870 nm per degree change in temp between mode hops

\[
m \frac{\lambda_m}{2n} = L
\]

\[
\frac{d\lambda_m}{dT} = \frac{d}{dT} \left( \frac{2Ln}{m} \right) \approx \frac{2L}{m} \frac{dn}{dT}
\]

\[
\frac{d\lambda_m}{dT} \approx \frac{\lambda_m}{n} \frac{dn}{dT} = \frac{870nm}{3.7} \left( 1.5 \times 10^{-4} K^{-1} \right) = 0.035 \frac{nm}{K}
\]
Steady State Semiconductor Rate Equations

- Rate of electron injection by current = rate of spontaneous emissions + rate of stimulated emissions
  \[ \frac{I}{edLW} = \frac{n}{\tau_{sp}} + CnN_{ph} \]

- Rate of coherent photon loss in the cavity = rate of stimulated emissions
  \[ \frac{N_{ph}}{\tau_{ph}} = CnN_{ph} \]
  - \( N_{ph} \) is the coherent photon concentration in the active layer
  - \( n \) is the injected carrier concentration
  - \( \tau_{sp} \) is the spontaneous recombination time
  - \( \tau_{ph} \) is the average time for a photon to be lost in the cavity due to transmission through the end faces, scattering, and absorption in the semiconductor
  - \( \alpha_t \) is the total attenuation coefficient representing all these loss mechanisms
  - Power in a light wave in the absence of amplification decreases as \( \exp(- \alpha_t x) \)
  - This is equivalent to a decay time of \( \exp(- t/ \tau_{ph}) \)
  - Where \( \tau_{ph} = n/(C\alpha_t) \)

- Above the threshold
  \[ \frac{I - I_{th}}{edLW} = Cn_{th}N_{ph} \]

- Coherent photon concentration
  \[ N_{ph} = \frac{\tau_{ph}}{ed} (J - J_{th}) \]

- Laser diode equation
  \[ P_o = \frac{\left(\frac{1}{2} N_{ph}\right)Cavity\ _volume\ (photo\ _energy)}{\Delta t} \]
  \[ P_o = \frac{hc^2 \tau_{ph} W(1-R)}{2en\lambda} (J - J_{th}) \]

Simplified and idealized description of a semiconductor laser diode based on rate equations. Injected electron concentration \( n \) and coherent radiation output power \( P_o \) vs. diode current \( I \).

\[ n_{th} = \frac{1}{C\tau_{ph}} \quad I_{th} = \frac{n_{th}edLW}{\tau_{sp}} \]

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Light Emitters for Optical Fiber Communications

- Choice of light source depends on communication distance and bandwidth required
- For short haul applications, such as local networks, LEDs are preferred because they are simpler to drive, cheaper to produce, have a longer lifetime, and provide the necessary output power even though the output spectrum is broader.
- LEDs are used in multimode and graded index fibers because the dispersion arising from finite linewidth of the output spectrum is not a major concern.
- For long haul and wide bandwidth communications, Laser diodes are used because of their narrow linewidth and high output power.
- Output spectrum of a laser diode can be very narrow (0.01 nm – 0.1 nm).
- Very fast operation defined by the rise time associated with inversion in a laser diode make it more amenable for high speed applications even when wide bandwidths are required.

Typical optical power output vs. forward current for a LED and a laser diode.

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Distributed Bragg Reflection for Single Mode Lasers

- Ensure single mode radiation in the laser cavity is to use frequency selective mirrors at the cleaved surfaces.
- Distributed Bragg reflector is a mirror that has been designed a reflective Bragg grating.
- Reflected wave occurs only when the wavelength corresponds to twice the corrugation periodicity, $\Lambda$.
- The diffraction order of the reflector is integer, $q = 0, 1, 2, ...$
- $N$ = refractive index of the mirror.
- Bragg wavelength of the mirror output is $\lambda_B$.

\[ q \frac{\lambda_B}{n} = 2\Lambda \]

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Distributed Feedback Laser (DFB)

- In a DFB laser, the corrugating grating is called the guiding layer and rest on top of the active layer.
- The pitch of the corrugation provides optical gain at the Bragg wavelength, $\lambda_B$.
- Traveling waves are excited by the active layer and couple to the guiding layer as they reflect back and forth across the grating to generate allowed DFB modes that are not exactly matched to the Bragg wavelength, but are placed symmetrically just off the ideal mode of the guiding layer at $\lambda_m$.

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1)$$

(a) Distributed feedback (DFB) laser structure. (b) Ideal lasing emission output. (c) Typical output spectrum from a DFB laser.

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DFB Laser Example

• Consider a DFB laser that has a corrugation period of $\Lambda = 0.22 \, \mu m$ and a grating length, $L$, of 400 microns.
• Suppose that the effective refractive index of the medium is 3.5.
• Assume a first order grating and calculate the Bragg wavelength, the mode wavelengths, and their separation

Bragg wavelength

$$\lambda_B = \frac{2\Lambda n}{q} = \frac{2(0.22\, \mu m)(3.5)}{1} = 1.54\, \mu m$$

Symmetric mode wavelengths

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL} (m+1) = 1.54\, \mu m \pm \frac{(1.54\, \mu m)^2}{2(3.5)(400\, \mu m)} (0+1)$$

$$\lambda_0 = 1.5392\, \mu m \quad or \quad 1.5408\, \mu m$$

Wavelengths are separated by 1.7 nm. Due to some symmetry, only one mode will appear in the output and for the most practical purposes the mode wavelength can be taken as $\lambda_B$. 
Cleaved Coupled Cavity Laser

- Device has two different optical cavities of length L and D.
- Each laser cavity is pumped by a different current.
- Only modes resonant in both cavities are allowed to resonate through the entire device, allowing the engineer to tune out certain modes from one or both independent laser diodes.
- Why pump both the cavities? Ans. Allowed modes in an unpumped cavity will undergo recombination if the device is not driven.
Quantum Well (QW) Devices

- Device with an ultra thin (50nm) narrow bandgap active region between two wider bandgap semiconductors
- Assume that in QW devices that the lattice match so that all the semiconductors have the same lattice constant $a$ so that crystalline defects are minimized
- Bandgap changes at the interface are therefore only due to discontinuities between $E_c$ and $E_v$ of the differing materials yielding discrete allowable quantum states that can be solved as “particle in a box” type problems.

A quantum well (QW) device. (a) Schematic illustration of a quantum well (QW) structure in which a thin layer of GaAs is sandwiched between two wider bandgap semiconductors (AlGaAs). (b) The conduction electrons in the GaAs layer are confined (by $E_c$) in the $x$-direction to a small length $d$ so that their energy is quantized. (c) The density of states of a two-dimensional QW. The density of state is constant at each quantized energy level.

Energy in a quantum well

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{2m_e}{\hbar} [E - V(x)] \Psi = 0$$

$$E = E_c + \frac{h^2 n_x^2}{8m_e d^2} + \frac{h^2 n_y^2}{8m_e D_y^2} + \frac{h^2 n_z^2}{8m_e D_z^2}$$

$n, n_y, n_z = 1, 2, 3, ...$

Note: potential energy barrier of the conduction band is defined w.r.t. $E_c$
Different Quantum Wells Types Based on Geometry

Image from Chapter 16, of Fundamentals of Photonics, 2nd ed. By Saleh and Teich cc 2007 Wiley Interscience
Density of States from our Particle in a Box Solution (QW Device)

$E_{c}$, $E_{v}$, $E_{g}$

$E_{g2}$, $E_{g1}$, $E_{e1}$

$E_{e2}$, $E_{e2} n = 2$, $n = 1$

$l = 2, k = 0$

$l = 1, k$

$l = 1, k = 0$

$\rho_{QW}(E)$

$\rho_{3D}(E)$

$\hbar \omega_{0}$

$E_{1c} = E_{g} + \frac{\hbar^{2} \pi^{2}}{2m_e L_z^{2}}$

$E_{2c} = E_{g} + \frac{2\hbar^{2} \pi^{2}}{m_e L_z^{2}}$

Energy

Figure from Chapter 16  Photonics, 6th edition  Yariv and Yeh  2007 Oxford University Press
Energy Spectrum in a Quantum Well (SQW)

In single quantum well (SQW) lasers electrons are injected by the forward current into the thin GaAs layer which serves as the active layer. Population inversion between $E_1$ and $E'_1$ is reached even with small forward current which results in stimulated emissions.

$h\nu = E_1 - E'_1$

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Example: A GaAs QW

- GaAs QW
- Effective electron mass is $m_e^* = 0.07m_e$
- What are the first two electron energy levels for a QW of thickness 10 nm?
- What is the hole energy below $E_v$ if the effective electron mass of the hole, $m_h^* = 0.5m_e$?
- What is the emission wavelength w.r.t. bulk GaAs which as an energy bandgap of 1.42 eV?

$$\varepsilon_n = \frac{\hbar^2 n^2}{8m_e^* d^2} = 0.0537eV$$

$$\varepsilon_n' = \frac{\hbar^2 n^2}{8m_h^* d^2} = 0.0075eV$$

$$\lambda_g = \frac{hc}{E_g} = \frac{1240eV \times nm}{1.42eV} = 874nm$$

$$\lambda_{QW} = \frac{hc}{E_g + \varepsilon_n + \varepsilon_n'} = \frac{1240eV \times nm}{(1.42 + 0.0527 + 0.0075)eV} = 839nm$$

- Difference in emission wavelength between a bulk GaAs LD and a QW LD is 35 nm

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**Figure 16.1** The layered structure and the bandedges of a GaAlAs/GaAs/GaAlAs quantum well.

Cc 2007 Photonics, 6th edition Yariv and Yeh (Oxford University Press)
Multiple Quantum Well (MQW) Lasers

- Discrete states in MQW devices that have thick barrier layers generate increased optical intensity at the same wavelength predicted by SQW devices.
- However if the barrier layer thickness is very thin (10 – 20 nm or so) then tunneling of quantum states between barriers provides coupling mechanisms that must be accounted for.
- Tunneling allows for the production of minibands within the bound quantum DOS. These minibands are the spread of the of the single quantum band that allows for electron energies to spread due to interactions between isolated quantum energy states within each active layer.

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Image from Chapter 16, of Fundamentals of Photonics, 2nd ed. By Saleh and Teich cc 2007 Wiley Interscience
Quantum Mechanical Tunneling

- Truly quantum phenomenon
- States that a quantum wave has a finite probability of passing through an infinite potential barrier into a neighboring state.
- The transmission of the wave exponentially decays with distance and the size of the barrier potential.
- For QW devices, the barrier potential is the difference between the conduction or valance band peaks between the active and cladding regions of the diode junction.
- The potential difference in AlGaAs/GaAs devices is:
  \[ V_o = E_{c_{AlGaAs}} - E_{c_{GaAs}} \approx 0.3 \text{ eV} \]

- Results of tunneling produce a smearing of energy states available in MQW devices.

\[ \frac{\partial^2 \Psi}{\partial x^2} + \frac{2m_e}{\hbar} \left[ E - V(x) \right] \Psi = 0 \]

\[ \Psi_1(x) = A_1 \exp(jK_1x) + B_1 \exp(-jK_1x) \]

\[ \Psi_2(x) = A_2 \exp(K_2x) + B_2 \exp(-K_2x) \]

\[ \Psi_3(x) = A_3 \exp(jK_3x) + B_3 \exp(-jK_3x) \]

\[ K_1 = \sqrt{\frac{8\pi^2 m E}{\hbar}} = ml \]

\[ K_2 = \sqrt{\frac{8\pi^2 m}{\hbar} (V_o - E)} \]

\[ T \approx 16 \left( \frac{E}{V_o} \right) \left( 1 - \frac{E}{V_o} \right) \exp(-2K_2a) \]
Vertical Cavity Surface Emitting Lasers (VCSELS)

- Alternating layers of low and high index above and below the QW region creates a distributed Bragg reflector of dielectric mirrors.
- The mirrors are needed to match the optical gain lost by the short cavity length. Thus with the mirrors the light passes through the cavity some 20-30 times to obtain a desired reflectance of 99%.
- The high reflectance increases the geometric component of the gain required for laser emission.

A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).

Figure 16.14 The field distribution of the laser mode inside a vertical cavity laser with \( L = \frac{\lambda}{n} \) with three quantum wells. Note the evanescent decay of the field envelope inside the Bragg mirrors and the constant-amplitude standing wave between the mirrors.

Constructive interference of partially reflected waves of wavelength, \( \lambda \), at the interface:

\[
 n_1d_1 + n_2d_2 = \frac{\lambda}{2}
\]
VCSEL Attributes

- VCSEL active layers are generally very thin
  - 0.1 um and comprised of MQW for improved threshold current
- The device is comprised of epitaxially deposited layer on a suitable substrate which is transparent in the emission wavelength
- Ex. 980 nm VCSEL devices
  - InGaAs is the active layer
  - GaAs is the substrate
  - AlGaAs with different compositions comprise the dielectric mirror stack
  - The top stack is then etched after all the layers have been deposited to create the inverted T shape presented in the previous slide
- In practice, current flowing through the dielectric mirrors gives rise to an undesired voltage drop that makes the device **VERY sensitive to failure from electrostatic discharge**. In fact, this is the most common failure mode during VCSEL operation and installation.
- The vertical cavity and thus the emitted beam is generally circular in cross section
- The height of the vertical cavity is several microns. Thus the longitudinal mode separation is sufficiently large to allow only one mode of operation. However lateral modes may be present in certain cavity geometries
- In practice VCSELS have several lateral modes but the spectral width is only ½ nm which is substantially less than the longitudinal modes of a DFB or ELD.
- Also, VCSELS have an average beam divergence of about 8-12° depending on their fabrication and materials used
- Dual wavelength VCSEL emission is obtained by operating at high currents.
Optical Laser Amplifiers

- Laser wavelength is matched to that of an input light signal pumped into the active region of a and edge emitting laser diode. Also, the length of the device should be matched to optimize cavity resonance for the FP case.

- Antireflective coating on the cleaved edges of the ELD reduce internal reflections and prevent optical resonance within the LD. Since optical resonance is a key requirement for laser-oscillations, the device itself fails to operate as a laser. Instead, as light passes through the optical region, it becomes amplified by induced stimulated emissions and leaves the cavity with as much as 20 dB. Gain.

- Fabry-Perot cavities operated below the threshold current can also be used. In the F-P resonator case, partial mirrors improve reflection and promote gain in the waveguide. However there is current pumped through the resonator to produce laser operation. Stimulate emissions from the LED operation condition boost the output signal. Output gains are higher than Traveling wave amplifiers, but devices are less stable.

Simplified schematic illustrations of two types of laser amplifiers

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Figure 15.22 A GaAs n-channel field-effect transistor integrated monolithically with a buried heterostructure GaAs/GaAlAs laser. The application of a gate voltage is used to control the bias current of the laser. This voltage can oscillate and modulate the light at frequencies $>10$ GHz. (After Reference [38].)
Figure 15.23 A monolithically integrated optoelectronic repeater containing a detector, transistor current source, a FET amplifier, and a laser on a single-crystal GaAs substrate. (After Reference [39].)
Figure 15.24 A monolithic circuit containing a tunable multisection InGaAsP/InP 1.55 μm laser employing multiquantum well (MQW) gain section, a passive waveguide for an external input optical wave, and a directional coupler switch for combining the laser output field and that of the external input at the output ports. (After Reference [41].)
Figure 15.25 An optoelectronic integrated circuit composed of three ~$1.5 \, \mu\text{m}$ InGaAs/InP distributed feedback lasers each tuned to a slightly different wavelength. The three wavelengths are fed into a single waveguide and amplified in a single amplifying section. (After Reference [42].)