1. Stimulated Emission and Photon Amplification

(a) Absorption  (b) Spontaneous emission  (c) Stimulated emission
The Principle of LASER

**Example: Solid State Laser**

The principle of the LASER. (a) Atoms in the ground state are pumped up to the energy level \( E_3 \) by incoming photons of energy \( h\nu_{13} = E_3 - E_1 \). (b) Atoms at \( E_3 \) rapidly decay to the metastable state at energy level \( E_2 \) by emitting photons or emitting lattice vibrations; \( h\nu_{32} = E_3 - E_2 \). (c) As the states at \( E_2 \) are long-lived, they quickly become populated and there is a population inversion between \( E_2 \) and \( E_1 \). (d) A random photon (from a spontaneous decay) of energy \( h\nu_{21} = E_2 - E_1 \) can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.
The Principle of **OPTICAL FIBER AMPLIFIERS**

**Er+3 Doped Glass Fiber**

Energy diagram for the Er³⁺ ion in the glass fiber medium and light amplification by stimulated emission from $E_2$ to $E_1$. Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations).

A simplified schematic illustration of an EDFA (optical amplifier). The erbium-ion doped fiber is pumped by feeding the light from a laser pump diode, through a coupler, into the erbium ion doped fiber.
The Principle of GAS LASERS:

The He-NE LASER

Flat mirror (Reflectivity = 0.999)  Concave mirror (Reflectivity = 0.985)

Very thin tube

He-Ne gas mixture

Laser beam

Current regulated HV power supply

He

\((1s^12s^1)\)

\(20.61\) eV

Electron impact

Ground states

\((1s^2)\)

\((2p^53s^1)\)

Collisions

\(20.61\) eV

\(2p^53p^1\)

\(20.66\) eV

\(632.8\) nm

Lasing emission

\((2p^53s^1)\)

\(~600\) nm

Fast spontaneous decay

Collisions with the walls

Ne

\((2p^6)\)

\((2p^55s^1)\)

The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).
STIMULATED EMISSION RATE and EINSTEIN COEFFICIENTS
PROPERTIES OF LASER LIGHT

1. Coherence

2. Beam Divergence (Collimation)
3. Spectral Purity

(a) Optical gain vs. wavelength characteristics (called the optical gain curve) of the lasing medium. (b) Allowed modes and their wavelengths due to stationary EM waves within the optical cavity. (c) The output spectrum (relative intensity vs. wavelength) is determined by satisfying (a) and (b) simultaneously, assuming no cavity losses.
Optical gain between FWHM points $\delta \lambda_m$ and Cavity modes.

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 $\Delta \lambda_{1/2}$. 

(a) 5 modes
(b) 4 modes
LASER OSCILLATION CONDITIONS

A. Optical Gain Coefficient

(a) A laser medium with an optical gain (b) The optical gain curve of the medium. The dashed line is the approximate derivation in the text.
B. Threshold Gain $g_{\text{th}}$

Steady state EM oscillations

Reflecting surface

$P_f$ $P_i$

$E_f$ $E_i$

$x$

$R_1$

$R_2$

$L$

$(N_2 - N_1)$ and $P_o$

$(N_2 - N_1)_{\text{th}}$

Threshold population inversion

$P_o = \text{Lasing output power}$

Threshold pump rate

Pump rate
C. Phase Condition and Laser Modes

Laser Modes (a) An off-axis transverse mode is able to self-replicate after one round trip. (b) Wavefronts in a self-replicating wave (c) Four low order transverse cavity modes and their fields. (d) Intensity patterns in the modes of (c).
The Principle of **THE LASER DIODE**

**Population Inversion via Carrier Injection and Recombination**

(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.

(b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.
GaAs Homojunction Laser Diode

Typical output optical power vs. diode current ($I$) characteristics and the corresponding output spectrum of a laser diode.
Double Heterostructure Laser Diode:
1. Carrier Recombination Confinement,
2. Photon Confinement

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the p-GaAs layer, the active layer.

(c) Higher bandgap materials have a lower refractive index.

(d) AlGaAs layers provide lateral optical confinement.
Double Heterostructure Laser Diode with Stripe Contact:

1. Carrier Recombination Confinement,
2. Photon Confinement
3. Carrier Injection Current Confinement

Schematic illustration of the structure of a double heterojunction stripe contact laser diode
Buried Double Heterostructure Laser Diode

1. **Carrier Recombination Confinement** (full cross section control)
2. **Photon Confinement** (full cross section control) (“index guided”)
3. **Carrier Injection Current Confinement** (full cross section control)

These laser diodes can operate in single mode because of full photon confinement and small lateral dimensions of the optical fiber-like cavity formed for the photons propagating inside.
1. Coherence

2. Modes (lateral and longitudinal)

3. Beam Divergence (Collimation)
4. Electrical Chs. And Optical Output Power and Spectrum

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)
3. Mode Hopping

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.
STEADY STATE SEMICONDUCTOR RATE EQUATIONS
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 $I$.
Typical optical power output vs. forward current for a LED and a laser diode.

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Figure 4.1
(a) Distributed Bragg reflection (DBR) laser principle. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves $A$ and $B$ interfere constructive when $q(\lambda_B/2n) = \Lambda$.

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Figure 4.2
(a) Distributed feedback (DFB) laser structure. (b) Ideal lasing emission output. (c) Typical output spectrum from a DFB laser.

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**Figure 4.3**
Cleaved-coupled-cavity (C³) laser

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**Figure 4.4**
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 $\frac{1}{2} E_C$) 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 states is constant at each quantized energy level.

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Figure 4.5
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 a small forward current which results in stimulated emissions.

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**Figure 4.6**
A multiple quantum well (MQW) structure. Electrons are injected by the forward current into active layers which are quantum wells.

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Figure 4.7
A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).

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Figure 4.8
Simplified schematic illustrations of two types of laser amplifiers

(a) Traveling wave amplifier

(b) Fabry-Perot amplifier

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Figure 4.9
A highly simplified illustration of holography. (a) A laser beam is made to interfere with the diffracted beam from the subject to produce a hologram. (b) Shining the laser beam through the hologram generates a real and a virtual image.

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Figure 4.10
Various lasing transitions in the He-Ne laser

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**Figure 4.11**
The Ar-ion laser energy diagram

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Figure 4.12
The energy band diagram of a degenerately doped $p$-$n$ with a sufficiently large forward bias to just cause population inversion where $A$ and $B$ overlap.

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**Figure 4.13**