4. STIMULATED EMISSION DEVICES : LASERS

4.1. Stimulated emission and photon amplification

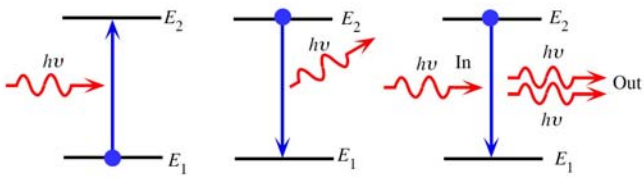
→ Absorption

→ Spontaneous emission : $h\nu = E_2 - E_1$

→ Stimulated emission

- In phase
- Same direction
- same energy
- same polarization

} with the incoming photon



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Absorption, spontaneous (random photon) emission and stimulated emission.

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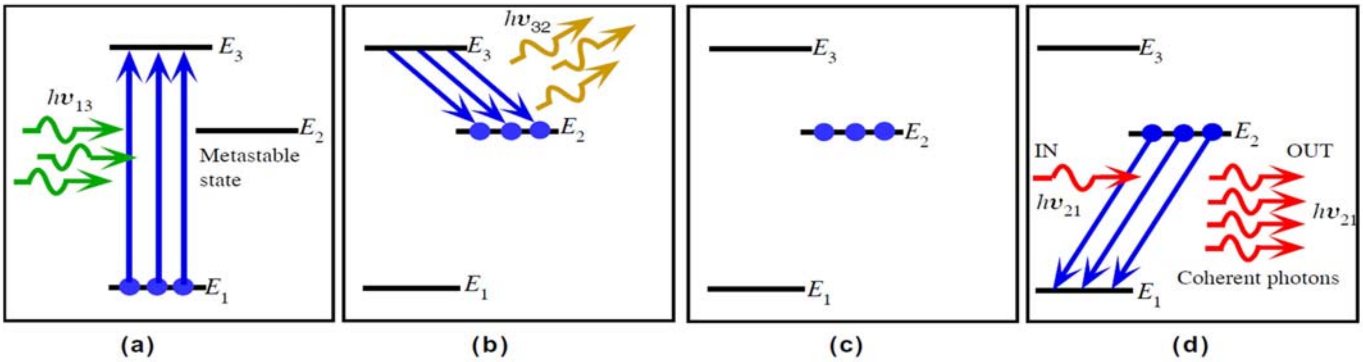
Figure 4.1

→ The majority of atoms at the state E_2 → population inversion.
If this were not the case, incoming atoms would be absorbed by the atoms at E_1.

Three energy-level system.



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 $h\upsilon_{13} = E_3 – E_1$. (b) Atoms at E_3 rapidly decay to the metastable state at energy level E_2 by emitting photons or emitting lattice vibrations; $h\upsilon_{32} = E_3 – E_2$. (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 $h\upsilon_{21} = E_2 – E_1$ 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.

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Figure 4.2

→ Exciting the atoms to E_3 → pumping.

→ Decay RAPIDLY to E_2 (the state at E_2 is a long-lived state)

→ Population inversion

→ Once one atom decays spontaneously from E_2 to E_1, which results in an avalanche effect of stimulated emission process.

→ $E_2 \to E_1$ → LASING EMISSION

4.2. Stimulated emission rate and Einstein coefficients

upward transition rate: (from $E_1 \to E_2$)

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

$\rho(h\nu)$ → photon energy density at $h\nu$

N_1 → # of atoms per unit volume

B_{12} → Einstein B_{12} coefficient

downward transition rate: (from $E_2 \to E_1$)

$$R_{21} = \underbrace{A_{21} N_2}_{\text{spontaneous emission term}} + B_{21} N_2 \rho(h\nu)$$

A_{21}, B_{21} → Einstein coefficients

To find the coefficients A_{21}, B_{12}, B_{21}; - THERMAL EQB. (NO EXTERNAL EXCITATION)

$$R_{12} = R_{21}$$

Boltzmann statistics → $N_2 = N_1 \exp\left(-\frac{E_2 - E_1}{kT}\right)$

in thermal eqb., photon en.-dens. is given by "Planck's blackbody radiation distribution law."

$$\rho_{eq}(h\nu) = \frac{8\pi h \nu^3}{c^3\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]}$$

We can show that

$$B_{12} = B_{21}$$

and

$$\frac{A_{21}}{B_{21}} = 8\pi h \nu^3 / c^3$$

Now consider the ratio stimulated to spontaneous em. rates:

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} = \frac{B_{21} N_2 \rho(h\nu)}{A_{21} N_2} = \frac{B_{21}\rho(h\nu)}{A_{21}}$$

OR

$$\boxed{\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} = \frac{c^3}{8\pi h \nu^3}\rho(h\nu)}$$

The ratio of stimulated emission to absorption:

$$\boxed{\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_2}}$$

Two important conclusions

→ For stimulated emission we need "population inversion" we must have an optical cavity to concentrate the photons.

→ To achieve population inversion we depart from thermal eqb.

∴ $N_2 > N_1$ implies a negative absolute temp. The laser principle is based on non-thermal eqb.

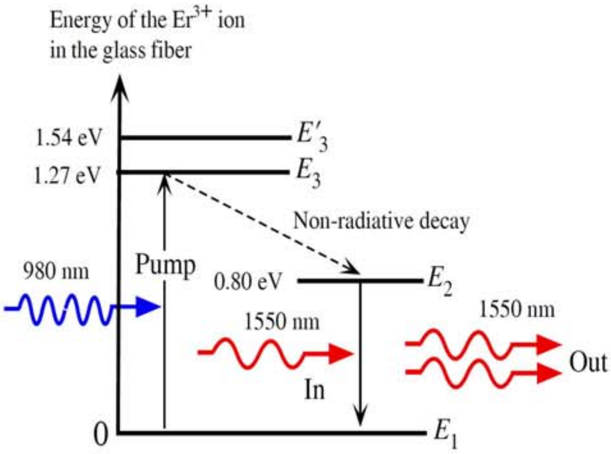
4.3. Optical Fiber Amplifiers

Erbium (Er^{3+} ion) doped fiber amplifier ~ EDFA

The core of an optical fiber is doped with Er^{3+} ions

Host fiber core is based on SiO_2-GeO_2

And other rare earth ions can be used such as Nd^{3+}



Energy diagram for the Er3+ ion in the glass fiber medium and light amplification by stimulated emission from E2 to E1. Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations)
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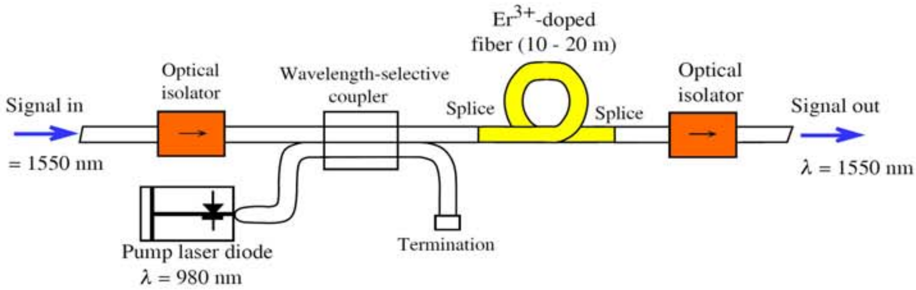
Figure 4.3



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.

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Figure 4.4

Net optical gain $\boxed{G_{op} = \underbrace{K}_{\text{constant}}(N_2 - N_1)}$

Since E_1, E_2 and E_3 are NOT single unique levels, there is a range of stimulated transitions from E_2 to E_1 corres. to 1525nm – 1565nm. → Bandwidth of 40nm

However the gain is not uniform throughout the whole bandwidth and must be flattened with special techniques.

The gain efficiency of EDFA is the max. optical gain per unit optical pumping power.

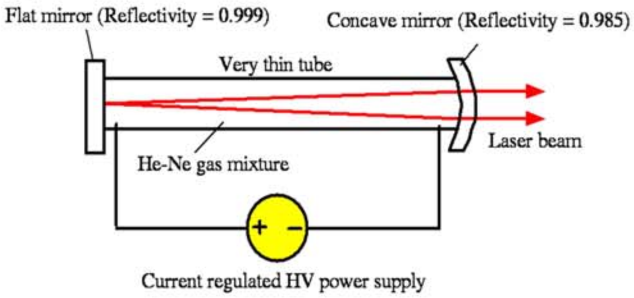
Typically ~ 8-10 dB/mW at 980nm

30 dB or 10^3 gain!

4.4. Gas Lasers : The He:Ne Laser

The actual emission at 632.8nm occurs from Ne atoms.

He atoms are used to excite Ne atoms by atomic collisions.



A schematic illustration of the He-Ne laser

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Ne: $1s^2\,2s^2 2p^6$ is an inert gas.

$$(2p^6) \xrightarrow{\text{excitation to 5s orbital}} (2p^5\,5s^1)$$

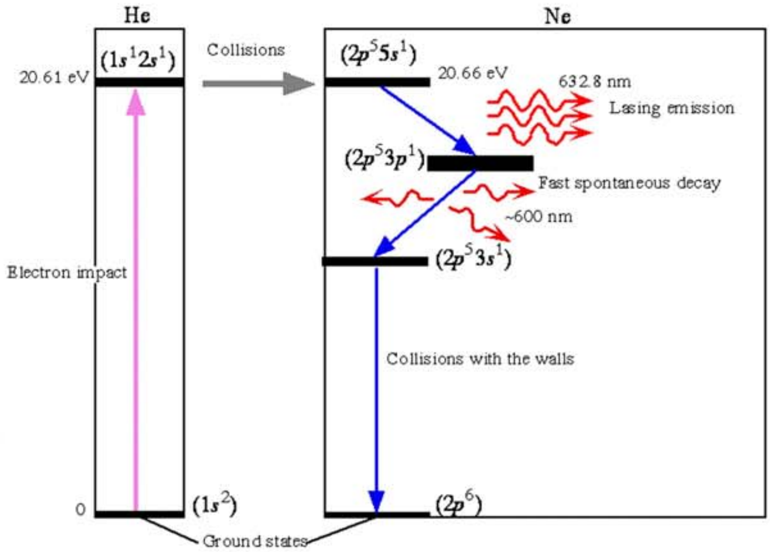
$$\text{He}: \; 1s^2 \Longrightarrow (1s^1 2s^1)$$

- Optical cavity is formed by mirrors
- Discharge is made by using dc or Rf high voltage.

→ metastable state

$$He + e^- \longrightarrow He^* + e^-$$

$$He^* + Ne \longrightarrow He + Ne^*$$



The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).

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- Energy of He^* atoms transfered to Ne atoms thru collisions.
- Large population inversion between $(2p^5 5s^1)$ and $(2p^5 3p^1)$ states of Ne atoms.
- A spontaneous emission from $(2p^5 5s^1) \longrightarrow (2p^5 3p^1)$ gives rise to an AVALANCHE of stimulated emission process.
- Transition from $2p^5 3p^1 \longrightarrow 2p^5 3s^1$ is spontaneous emission
- However from $2p^5 3s^1 \longrightarrow 2p^6$ (ground) is a long lasting transition.
- Transition to the ground level of Ne atom takes place by collisions with the wall of the tube. Since requiring repumping of electrons, a HeNe laser can not be manufactured with a larger tube diameter to increase the laser power.
- Lasing emission intensity (optical gain) increases the TUBE LENGTH.
- Two mirrors with 99.9% and 99% reflecting. The output lens
The less reflecting mirror is a concave one, and behaves a convergent lens.

Ex. 4.4.1. Efficiency of the HeNe laser

A typical 5mW low-power He-Ne is operating at 2000Vdc with a current of 7mA.
Efficiency of the laser ?

$$\text{Efficiency} = \frac{\text{Output Laser Power}}{\text{Input Electrical Power}} = \frac{5\times10^{-3}\,W}{(7\times10^{-3}A)(2000V)} = 0.036\,\%$$

Most of the HeNe lasers have efficiencies less than 0.1%.
However, what is important is the high concentration of photons.

5mW means ; $6.4\,kW\,m^{-2}$ if the beam diameter is 1mm.

4.5. The output spectrum of a Gas Laser

- Doppler broadening due to the random motion of gas molecules:

$$\nu_1 = \nu_0\left(1 - \frac{V_x}{c}\right) \quad \text{or} \quad \nu_2 = \nu_0\left(1 + \frac{V_x}{c}\right)$$

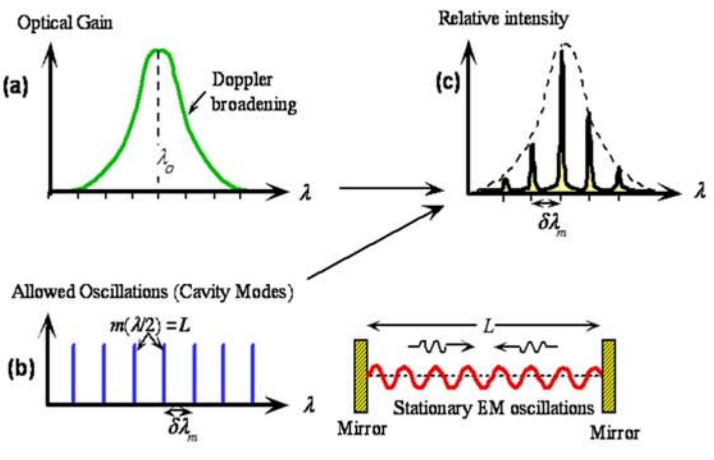
Doppler broadened linewidth $\rightarrow \Delta\nu = \nu_2 - \nu_1$

- $\lambda_0 \rightarrow$ central wavelength $\left(\lambda_0 = \frac{c}{\nu_0}\right)$
- for many gas lasers $\nu_2 - \nu_1 = 2\text{–}5\ \text{GHz}$ (corres. to 0.02Å for HeNe laser)

The linewidth $\Delta\nu_{1/2}$ between the half-intensity points

$$\Delta\nu_{1/2} = 2\nu_0\sqrt{\frac{2kT\ln(2)}{Mc^2}}$$

$$\boxed{\frac{1}{2}MV_x^2 = \frac{1}{2}kT}$$



(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.

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Fabry-Perot optical resonator

Laser Cavity Modes in a Gas Laser

$$\boxed{m\left(\frac{\lambda}{2}\right) = L}$$

Length of tube

mode number

Each possible standing wave satisfying $m\frac{\lambda}{2} = L$ is a cavity mode.

- These modes are axial or <u>longitudinal</u> modes.

Example 4.5.1. Doppler broadened linewidth.

He-Ne laser at $\lambda = 632.8$nm. If the temp is 127°C

Atomic mass of Ne is 20.2 g/mol. Tube length is 40cm

→ What is the linewidth?
→ what is mode number, m, of the central wavelength, λ_0?
→ separation between consecutive modes?
→ How many modes within $\Delta\nu_{1/2}$?

$$\Delta\nu_{rms} = \nu_0\left(1+\frac{V_x}{c}\right) - \nu_0\left(1-\frac{V_x}{c}\right) = \frac{2\nu_0 V_x}{c}$$

Kinetic Molecular Theory } $\quad V_x^2 = \frac{kT}{M}$

$$\boxed{M = \left(20.2\times10^{-3}\frac{kg}{mol}\right)\cdot\left(6.02\times10^{23}\,mol^{-1}\right) = 3.35\times10^{-26}\,kg}$$

$$V_x = \left[\frac{(1.38\times10^{-23}\,J/K)(127+273K)}{(3.35\times10^{-26}\,kg)}\right]^{1/2} = 405.8\ m/s$$

$$\nu_0 = \frac{c}{\lambda_0} = \frac{(3\times10^{8}\,m/s)}{(632.8\times10^{-9}\,m)} = 4.74\times10^{14}\,s^{-1}$$

The rms frequency bandwidth: $\rightarrow \Delta\nu_{rms} = \frac{2\nu_0 V_x}{c} = 1.282\ GHz$

The observed FWHM $\Delta\nu_{1/2}$ $\rightarrow \Delta\nu_{1/2} = 2\nu_0\left(\frac{2kT\ln 2}{Mc^2}\right)^{1/2} = 1.51\ GHz$ 0.18% wider

To get FWHM wavelength width $\Delta\lambda_{1/2}$, differenciate $\lambda = \frac{c}{\nu}$

$$\frac{d\lambda}{d\nu} = -\frac{c}{\nu^2} = -\frac{\lambda}{\nu}$$

$$\Delta\lambda_{1/2} \simeq \Delta\nu_{1/2} \left|-\frac{\lambda}{\nu}\right| = (1.51\times10^9\,Hz)\left(\frac{632.8\,nm}{4.74\times10^{14}\,s^{-1}}\right) \approx 0.0020\,nm$$

The width between half points of spectrum.

The rms linewidth would be $\Delta\lambda_{rms} = 0.0017\,nm$

Each mode satisfies $m\frac{\lambda}{2} = L$

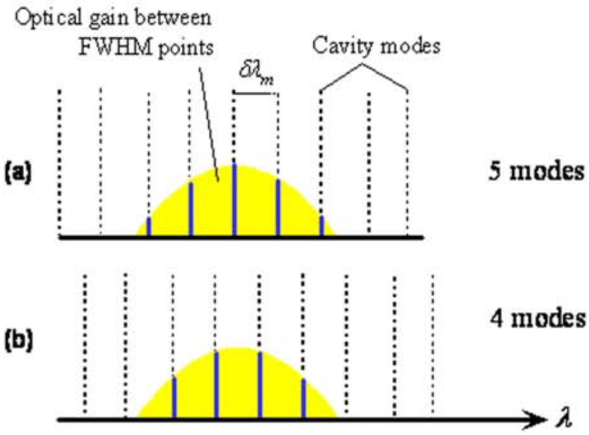
$$\hookrightarrow m_o = \frac{2\times0.4m}{632.8nm} = 1264222.5$$

→ In reality m_o has to be the closest integer

The separation $\delta\lambda_m = \frac{\lambda}{m} - \frac{\lambda}{m+1} = \frac{2L}{m} - \frac{2L}{m+1} \approx \frac{2L}{m^2}$

OR $\hookrightarrow \boxed{\delta\lambda_m = \frac{\lambda_o^2}{2L}}$

Therefore $\delta\lambda_m = \frac{632.8nm}{2\times0.4m} = 5.006\times10^{-13}\,m$ or $\boxed{0.501pm}$



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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$$\# \text{ of modes} = \frac{\text{Linewidth of spectrum}}{\text{Separation of two modes}} \approx \frac{\Delta\lambda_{1/2}}{\delta\lambda_m} = \frac{2.02pm}{0.501pm} = 4.03$$

we expect 4 or 5 modes within the linewidth !