Lecture 15

Stimulated Emission Devices- Lasers

- Stimulated emission and light amplification
- Einstein coefficients
- Optical fiber amplifiers
- Gas laser and He-Ne Laser
- The output spectrum of a gas laser
- Laser oscillation conditions
- Semiconductor lasers, (laser diodes)
- Rate equation*
- Light emitters for optical fiber communications
Stimulated Emission

- Electrons can absorb photons from medium
- Accelerated electrons emit light to return their ground state
- Spontaneous emission occurs through a relaxation process
- A photon can stimulate an electron to radiate in phase (coherent)
- Two levels is not enough to create population inversion!!
Einstein Coefficients

Absorption

\[ R_{12} = B_{12}N_1 \rho(\nu) \]

\[ -\frac{dN_1}{dt} \quad \text{Absorption} \]

Spontaneous emission

\[ R_{21} = A_{21}N_2 + B_{21}N_2 \rho(\nu) \]

\[ -\frac{dN_2}{dt} \quad \text{Spontaneous emission} \]

Stimulated emission

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

\[ B_{12} = B_{21} \]
Two Level Population Inversion??

Absorption

\[ R_{12} = B_{12}N_1 \rho(\nu) \]
\[ R_{12} = N_1 \left[ B \rho(\nu) \right] \]

Stimulated emission

\[ B_{12} = B_{21} \]
\[ R_{21} = A_{21}N_2 + B_{21}N_2 \rho(\nu) \]
\[ R_{21} = N_2 \left[ B \rho(\nu) \right] \]
A four energy level laser system
Nd$^{3+}$:YAG laser
(Yttrium Aluminate Garnate) YAG
Light Amplification

(a) Absorption

(b) Spontaneous emission

(c) Stimulated emission

\[ R_{12} = B_{12} N_1 \rho(\nu) \]

\[ R_{21} = A_{21} N_2 + B_{21} N_2 \rho(\nu) \]

\[ B_{12} = B_{21} \]

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

\[ \frac{R_{21} \text{ (stim)}}{R_{12} \text{ (absorp)}} = \frac{N_2}{N_1} \]

Population inversion

\[ \frac{R_{21} \text{ (stim)}}{R_{21} \text{ (spon)}} \propto \rho(\nu) \]

Optical cavity
Lecture 16

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Absorption Cross Section

Absorption

Optical power absorbed by an ion

\[ A \Delta l = - (I \sigma_{ab}) N_1 A \Delta x \]

Total Power Absorbed

\[ - \frac{\Delta l}{l \Delta x} = \sigma_{ab} N_1 = \alpha \]
Emission Cross Section

Stimulated optical power emitted by an ion

\[ = \text{Light intensity} \times \sigma_{\text{em}} \]

\[
\frac{\Delta l}{l \Delta x} = \sigma_{\text{em}} N_2
\]
Optical Gain Coefficient

Absorption

Stimulated emission

Definition

\[ g = \left[ \frac{\Delta l}{l \Delta x} \right]_{\text{net}} \]

\[ g = \sigma_{\text{em}} N_2 - \sigma_{\text{ab}} N_1 \]

\[ g = 0 \quad \text{No Gain!!} \]
Two Level Population Inversion??

\[ g = \sigma_{em}N_2 - \sigma_{ab}N_1 \]

\[ R_{12} = N_1 \left[ B\rho(v) \right] \sigma_{abs} \]

\[ R_{21} = N_2 \left[ B\rho(v) \right] \sigma_{em} \]

\[ \sigma_{abs} = \sigma_{em} \]
Optical Gain Coefficient

- Discrete energies turn into manifolds.
- **Absorption** can occur from any energy level.
- **Emission** occurs from the bottom of the $E_2$ manifold and top of $E_1$ manifold.
- Non-linear processes cause frequency dependent absorption and emission cross-sections.

\[
g = \sigma_{em} N_2 - \sigma_{ab} N_1
\]

\[
g(\nu) = \sigma_{em}(\nu) N_2 - \sigma_{ab}(\nu) N_1
\]

Optical Gain

\[
G = \exp(gL)
\]
Erbium Doped Fiber Amplifier (EDFA)

Signal in $\lambda = 1550$ nm

Optical isolator

PLD
Pump laser diode $\lambda = 980$ nm

Wavelength selective coupler

Splice A

$\text{Er}^{3+}$-doped fiber (10 - 20 m)

Splice B

Optical isolator

Signal out $\lambda = 1550$ nm

Termination
Erbium Doped Fiber Amplifier (EDFA)

- Optical amplifier is based on erbium (Er^{3+} ion)- doped fiber amplifier.
- Medium causes Stark Effect in silica-aluminate (SiO_3-Al_2O_3) or silica-germania (SiO_3-GeO_2)
- Energy bands occurs
- E_1-E_0 (30-40meV) population ratio 1 to 4. E_3 is narrow. E_2 is long-lived energy level (10ms)
Erbium Doped Fiber Amplifier (EDFA)

Definition:

\[ g = \left[ \frac{\Delta l}{l \Delta \chi} \right]_{\text{net}} \]

\[ g = \sigma_{\text{em}} N_2 - \sigma_{\text{ab}} N_1 \]

\[ g(\nu) = \sigma_{\text{em}}(\nu) N_2 - \sigma_{\text{ab}}(\nu) N_1 \]

Optical Gain:

\[ G = \exp(gL) \]
Erbium Doped Fiber Amplifier (EDFA)
EDFA Configurations

**Codirectional pumping**

**Counterdirectional pumping**
Typical characteristics of EDFA small signal gain in dB vs launched pump power for two different types of fibers pumped at 980 nm. The fibers have different core compositions and core diameter, and different lengths ($L_1 = 19.9$ m, and $L_2 = 13.6$ m)

Typical dependence of small signal gain $G$ on the fiber length $L$ at different launched pump powers. There is an optimum fiber length $L_p$.,
EDFA Configurations

Bidirectional pumping
Typical dependence of gain on the output signal strength for different launched pump powers. At high output powers, the output signal saturates, i.e. the gain drops.

\[ P_{dBm} = 10 \log \left( \frac{P_{mW}}{1 \ mW} \right) \]
Power Conversion Efficiency (PCE)

$$\eta_{PCE} = \frac{P_{sout} - P_{sin}}{P_{pin}} \approx \frac{P_{sout}}{P_{pin}}$$

$$\eta_{PCE} \approx \frac{\Phi_{sout}}{\Phi_{pin}} \times \frac{\lambda_p}{\lambda_s}$$

$$P \equiv \Phi_{\text{photon}} \frac{hc}{\lambda}$$

GAIN

$$G = \frac{P_{sout}}{P_{sin}} = 1 + \eta_{PCE} \left( \frac{P_{pin}}{P_{sin}} \right)$$

$$\eta_{\text{max}}_{PCE} \approx \frac{\lambda_p}{\lambda_s}$$

$$P_{sin} < (\frac{\lambda_p}{\lambda_s})P_{pin} / (G-1)$$
when $N_1$ is very small

Absorbed Pump Power
Absorbed Energy per Unit Time

$$\left( A L_p \right) \left( N_2 \right) \left( h \nu_p \right) / \tau_{sp}$$

Confinement factor

$$\Gamma P_p \approx A N h \nu_p L_p / \tau_{sp}$$

$$G = \exp(gL)$$

$N_2 = N_0$
EDFA Pump Equalization

**Definition**

\[ g = \left[ \frac{\Delta l}{l \Delta \chi} \right]_{\text{net}} \]

\[ g = \sigma_{em} N_2 - \sigma_{ab} N_1 \]

\[ g(\nu) = \sigma_{em}(\nu) N_2 - \sigma_{ab}(\nu) N_1 \]
Fiber Bragg grating has a Bragg grating written in the core of a single mode fiber over a certain length of the fiber. The Bragg grating reflects any light that has the Bragg wavelength $\lambda_B$, which depends on the refractive index and the periodicity. The transmitted spectrum has the Bragg wavelength missing.
EDFA Pump Equalization

Gain (dB)

$t_P = -15 \text{ dBm}$
$t_P = -9 \text{ dBm}$
$t_P = -5 \text{ dBm}$

Wavelength (nm)

Without gain flattening

Long period
Fiber Bragg gratings

In

$\lambda_1$

$\lambda_2$

Out

With gain flattening

Gain (dB)

$t_P = -15 \text{ dBm}$
$t_P = -9 \text{ dBm}$
$t_P = -5 \text{ dBm}$

Wavelength (nm)

EDFA Pump Equalization

EDFA1

EDFA2

OI

OI

WSC

WSC

Pump 1

980 nm

Pump 2

1480 nm

Gain (dB)

1 dB

1530 1540 1550 1560 1570

Wavelength (nm)
EDFA Noise

- Amplified spontaneous emission (ASE) noise in the output spectrum and the amplified signal.
- The dependence of NF and gain ($G$) on the input signal power level ($P_{\text{in}}$) for an EDFA under forward (codirectional) pumping.

$$NF = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}}$$

$$NF(\text{dB}) = 10 \log \left( \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}} \right)$$
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

THORLABS
He-Ne Laser Principles

- DC or RF High Voltage is used to create electrical discharge
- Collisions of energetic electrons with He results in He* ions.
- Metastable (long lasting) He* ions resonantly transfer their energy to Ne atoms
- Excited Ne atom ($2p^55s^1$) create a population inversion
- 4 states at $2p^55s^1$ and 10 states at $2p^53p^1$

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>543.5</th>
<th>594.1</th>
<th>612</th>
<th>632.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Green</td>
<td>Yellow</td>
<td>Orange</td>
<td>Red</td>
</tr>
</tbody>
</table>
- From \(2p^53p^1\) state Ne atom spontaneously decay to \(2p^53s^1\) state.
- \(2p^53s^1\) state is a metastable state.
- Excited Ne atoms at \(2p^53s^1\) state can relax through collisions with the walls.
- Tube diameter limits output powers.
- Optical cavity with a flat and concave mirror is used.
- Beam diameter 0.5-1 mm, divergence of few milliradians, power few milliwatts.
- Brewster windows for polarization selection.
He-Ne Laser Modes

Doppler broadening

Axial or longitudinal modes

Allowed Oscillations (Cavity Modes)

\[ \Delta v_{1/2} = 2v_o \sqrt{\frac{2k_B T \ln(2)}{Mc^2}} \]

\[ \lambda_{1/2} \approx \Delta v_{1/2} \lambda / \vartheta \]

\[ m \left( \frac{\lambda}{2} \right) = L \]

Optical Gain

Relative intensity

\[ \Delta \lambda_m \]

\[ m(\lambda/2) = L \]

Stationary EM oscillations

Mirror

Mirror

Longitudinal mode number
Doppler Effect (Source in Motion)

Source at rest

\[ f = \text{constant} = \frac{c}{\lambda} \]

Doppler Effect:

\[ \lambda' = \lambda - v_s T \]
\[ = \lambda - v_s \frac{\lambda}{v} \]
\[ = \lambda (1 - v_s / v) \]
\[ f' = \frac{v}{\lambda'} \]
\[ f' = f \frac{v}{v - v_s} \]