

Introduction to Laser Physics

Introduction to Laser Physics – Study Notes

1. What Is a Laser?

Term	Meaning
Laser	Light Amplification by Stimulated Emission of Radiation .
Coherent Light	Photons are in phase (constant phase relationship) and travel in the same direction.
Monochromatic	Emission at a very narrow wavelength band (?? ? ?).
Highly Directional	Beam divergence typically $< 1 \text{ mrad}$.

2. Fundamental Concepts

2.1. Atomic Energy Levels

- **Ground state (E_1)** – lowest energy level, most atoms occupy this at thermal equilibrium.
- **Excited state (E_2)** – higher energy level; population can be created by pumping.

2.2. Spontaneous vs. Stimulated Emission

Process	Trigger	Photon Characteristics
Spontaneous emission	Random decay of excited atom	Random phase, direction, and polarization
Stimulated emission	Incident photon with energy $h\nu = E_2 - E_1$	Emitted photon copies phase, direction, and polarization of the stimulating photon

2.3. Population Inversion

- Condition: $N_2 > N_1$ (more atoms in excited state than ground state).
- Required for net gain because stimulated emission must outbalance absorption.

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2.4. Gain Medium

- Material that provides the active transition (e.g., ruby crystal, Nd:YAG, semiconductor quantum wells, gas mixtures).
 - Characterized by **gain coefficient** $g(\lambda)$, which depends on wavelength, pump power, and temperature.
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3. Laser Cavity (Resonator)

Component	Function
Two mirrors (high reflectivity & partially transmitting)	Form standing wave optical resonator; define allowed longitudinal modes.
Optical cavity length L	Determines mode spacing: $\Delta \nu = c / (2L)$.
Mode selection	Achieved with apertures, etalons, or diffraction gratings to enforce single frequency operation.

3.1. Longitudinal Modes

- Integer number q of half wavelengths fits into cavity: $q \cdot \lambda / 2 = L$.
- Frequency of mode q : $\nu_q = q \cdot (c / 2L)$.

3.2. Transverse Modes

- Spatial field distribution described by **Hermite-Gaussian (TEM₀₀)** or **Laguerre-Gaussian** patterns.
 - Fundamental mode **TEM₀₀** gives the smallest divergence.
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4. Rate Equation Model (Simplified)

For a two-level system:

$$\left[\frac{dN_2}{dt} = R_{\text{pump}} - \frac{N_2}{\tau} - B_{21} \rho(\nu), (N_2 - N_1) \right]$$

$$\left[\frac{d\Phi}{dt} = B_{21} \rho(\nu), (N_2 - N_1) - \frac{\Phi}{\tau_c} \right]$$

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- (R_{pump}) – pump rate (atoms s^{-1}).
- (τ) – spontaneous lifetime.
- (B_{21}) – Einstein coefficient for stimulated emission.
- $(\rho(\nu))$ – photon density in the cavity.
- (γ)