REVIEW PRINCIPLE AND APPLICATION OF LASERS

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In Partial Fulfillment for the
Degree of Master of Science in Physics

By

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The undersigned hereby certify that they have read and recommend to the school of Graduate Studies of Addis Ababe University for acceptance a graduate project entitled "**REVIEW PRINCIPLE AND APPLICATION OF LASERS**" by **Tedla Giday** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Abstract

Light Amplification by Stimulated Emission of Radiation(LASER) is a mechanism for amplifying electromagnetic radiation, often visible light, via the process of stimulated emission. Coherence, monochromaticity,collimation, spectral brightness and high intensity are the main characteristics of laser light.

This project describes the basic aspects of a laser. It includes a quantitative discussion of the major properties, the different types of lasers, characteristics of laser light and applications of laser as well as the basic mechanisms of producing laser light. Moreover, the Einstein A and B coefficients and their historical derivation are reviewed. In addition, time-dependent perturbation theory is used as a tool in understanding how electromagnetic radiation interacts with atoms, causing transitions of its electrons among different energy levels.

Acknowledgements

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Chapter 1

Introduction

The word laser originally was the upper-case (LASER), the acronym for Light Amplification by Stimulated Emission of Radiation, wherein light broadly denotes electromagnetic radiation of any frequency, not only the visible spectrum, hence infrared laser, ultraviolet laser, X-ray laser, etc

The basic phenomena for laser emission, stimulated emission of radiation by excited atoms, was introduced by Albert Einstein as early as 1917 from thermodynamic speculation on the interaction of atoms with black body radiation.

The laser is a light source that exhibits unique properties. Since the first demonstration of a ruby laser by Maiman in 1960, there has been a phenomenal development in the field of lasers.

In 1917, Albert Einstein established the theoretical foundations for the Laser in a paper on the Quantum Theory of Radiation; via a re-derivation of Max Planck's law of radiation, conceptually based upon probability coefficients (Einstein coefficients) for the absorption, spontaneous and stimulated emission of electromagnetic radiation.

Laser light is different from conventional light in three ways. First, the light from laser contains only one color or wavelength and thats why it is called monochromatic.

Secondly, all the wavelengths are in phase because of this it is known as coherent. And thirdly, laser light beams are very narrow and can be concentrated on one tiny spot. This property makes it to be known as collimated.

Lasers dominate our modern world in a variety of forms ranging from tiny diode lasers in all CD and DVD players to large industrial lasers, used extensively for cutting and welding, example in automobile manufacturing. In fact, lasers are used in thousands of applications in every section of modern society, including consumer electronics, information and communications technology, entertainment, industry, the medical field and defense.

The laser triggered the photonics revolution and is the foundation of modern photonics. Modern laser research involves fundamental laser physics, creative development of novel laser concepts and advanced experimental work and diagnosis. All this can lead to the development of new lasers, which will fulfill the requirements of current and future demands in science and industry. [1-4]

In this project, the basic principles of laser operation and the mechanisms of interaction of radiation with matter (absorption, spontaneous and stimulated emission) will be discussed in the chapter 2. chapter 3 deals with the Einstein coefficients and rate equation for two and three level lasers, types and applications of lasers will be discussed in the chapter 4. Finally, the last chapter presents pulsed and continues wave lasers.

Chapter 2

Interaction of Radiation with Matter

Many of the properties of a laser may be readily discussed in terms of the absorption and emission processes which take place when an atomic system interacts with a radiation field. In the first decade of the last century Planck described the spectral distribution of thermal radiation, and in the second decade Einstein, by combining Planck's law and Boltzmann statistics, formulated the concept of stimulated emission. Einstein's discovery of stimulated emission provided essentially all of the theory necessary to describe the physical principle of the laser. [5-8]

2.1 Emission and absorption of radiation

The working principle of lasers is based on the interaction of radiation with matter. There are three mechanisms by which radiation and matter interact. These are absorption, spontaneous and stimulated emissions. Consider a two-level atom with upper level 2 and lower level 1. Moreover, we denote the energy eigenvalue and population density of levels 2 and 1 by E_2, N_2 and E_1, N_1 respectively as shown in Fig

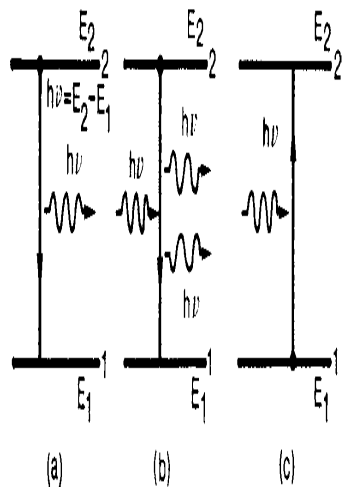

Figure 2.1: Schematic illustration of the three processes: (a) spontaneous and (b) stimulated emission and (c) absorption

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2.1.1 Spontaneous emission

occurs in the absence of external radiation. Instead a molecule in the excited state can relax to the ground state by spontaneously emitting a photon. Spontaneously emitted photons are emitted in all directions.

An atom in an upper level can decay spontaneously to the lower level and emit a photon of frequency ν_o. As far as the following discussion is concerned, the two levels could be any two out of the infinite set of levels possessed by the atom. It is convenient, however, to take level 1 to be the ground level.

Let us now assume that the atom is initially in the upper level 2. Since $E_2 > E_1$, the atom will tend to decay to level 1. The corresponding energy difference, $E_2 - E_1$, must therefore be released by the atom. When this energy is delivered in the form of an electromagnetic wave, the process will be called spontaneous(radiative) emission. The frequency ν_0 of the radiated wave is then given by the well known expression

$$\nu_0 = \frac{E_2 - E_1}{h} \tag{2.1.1}$$

where h is Planck's constant. Spontaneous emission is therefore characterized by the emission of a photon of energy $h\nu_0 = E_2 - E_1$, when the atom decays from level 2 to level 1 (Fig. 2.1a) in the absence of external radiation.

Note that radiative emission is just one of the two possible ways for the atom to decay. The decay can also occur in a non-radiative way. In this case the energy difference $E_2 - E_1$ is delivered in some form of energy other than electromagnetic radiation(e.g.,it may go into kinetic or internal energy of the surrounding atoms or molecules). This phenomenon is called non-radiative decay. [1]

2.1.2 Stimulated emission

Let us now suppose that the atom is found initially in level 2 and that an electromagnetic wave of frequency $\nu = \nu_o$ (i.e., equal to that of the spontaneously emitted wave) is incident on the material (Fig. 2.1b). Since this wave has the same frequency as the atomic transition frequency, there is a finite probability that this wave will force the atom to undergo the transition from level 2 to level 1. In this case the energy difference $E_2 - E_1$ is delivered in the form of an electromagnetic wave that adds to the incident one. This is the phenomenon of stimulated emission. There is a fundamental difference between the spontaneous and stimulated emission processes. In the case of spontaneous emission, the atom emit an electromagnetic wave that has no definite phase relation with that emitted by another atom. Furthermore, the wave can be emitted in any direction. In the case of stimulated emission, since the process is forced by the incident electromagnetic wave, the emission of any atom adds in phase to that of the incoming wave and along the same direction.

2.1.3 Absorption of radiation

An atom in a lower level absorbs a photon of frequency ν and makes a transition to an upper level. Let us now assume that the atom is initially in level 1 (Fig. 2.1c). If this is the ground level, the atom will remain in this level unless some external stimulus is applied to it. We shall assume, then, that an electromagnetic wave of frequency $\nu = \nu_o$ is incident on the material.

In this case there is a finite probability that the atom will be raised to level 2. The energy difference $E_2 - E_1$ required by the atom to undergo the transition is obtained from the energy of the incident electromagnetic wave. This is the absorption process. If a collection of atoms are in the excited state, spontaneous decay events to the ground state will occur at a rate proportional to N_2, the number of atoms in the excited state.

The energy difference between the two states ΔE_{21} is emitted from the atom as a photon of frequency υ as given by the frequency-energy relation $\nu = \frac{\Delta E_{21}}{h}$.

If N_1 is the number density of atoms in state 1 then the change in the number density of atoms in state 2 per unit time due to spontaneous emission will be

$$\frac{dN_2}{dt} = -A_{21}N_2 \tag{2.1.2}$$

where A_{21} is a constant of proportionality with dimensions s^{-1}, called Einstein coefficient for spontaneous emission. The same process results in increasing of the population of the state 1 and hence

$$\frac{dN_1}{dt} = A_{21}N_2 \tag{2.1.3}$$

Spontaneous emission is characterized by the lifetime of the electron in the excited state, after which it will spontaneously return to the lower state and radiate away the energy. This can occur in the absence of an electromagnetic field. The solution of Eq(2.1.2) is expressible as

$$N_2(t) = N_2(0)e^{-A_{21}t} = N_2(0)e^{\frac{-t}{\tau_{21}}} \tag{2.1.4}$$

where $\tau_{21} = A_{21}^{-1}$ is the lifetime for spontaneous radiation of level 2 and N_0 is number of atoms in ground state . This radiation lifetime is equal to the reciprocal of the Einstein coefficient.That is

$$\tau_{21} = A_{21}^{-1} \tag{2.1.5}$$

In general, reciprocal of the transition probability of a process is called its lifetime. The photons are emitted stochastically and there is no fixed phase relationship between photons emitted from a group of excited atoms; in other words, spontaneous emission is in coherent. In the absence of other processes, the number of atoms in the excited state at time t, is given by eq (2.1.4)

2.2 Basic Principles of Laser Operation

2.2.1 Components of a Laser

They are three basic components of laser. These are- a) Active medium, b) Pump source and c) Optical resonator. [5-8]

a) **The Active Medium**

Active medium is collection of atoms or molecules which can be excited in to a population inversion situation and can have electro -magnetics radiation. The active medium is excited by the external energy source(pump source) to produce population inversion. Semiconductors, organic dyes, gases (He, Ne, CO_2, etc), solid materials Yttrium-Aluminium-Garnet sapphire (ruby) etc.) are usually used as lasing materials and often lasers are named for the ingredients used as medium.

b)**Pump Source**

The pump source is an energy source to supply the energy needed for raising the system to the excited state. Pumping can be done in two ways - electrical discharge method and optical method. Examples of pump sources include electrical discharges, flash lamps, arc lamps, light from another laser, chemical reactions and even explosive devices. The type of pump source used principally depends on the gain medium and this also determines how the energy is transmitted to the medium.

A helium-neon (He-Ne) laser uses an electrical discharge in the helium-neon gas mixture, a Ytterbium :Yttrium-Aluminium-Garnet laser uses either light focused from a xenon flash lamp or diode lasers and excimer lasers use a chemical reaction.

c) **Optical Resonator**

In most of the systems, optical resonator consists of two mirrors. One mirror is fully reflective and other is partially reflective. Both the mirrors are set up on optic axis, parallel to each the other. The active medium is put in the optical cavity between the two mirrors. This arrangement only filters those photons which came along the axis and others are reflected by the mirrors back into the medium, where it may be amplified by stimulated emission.

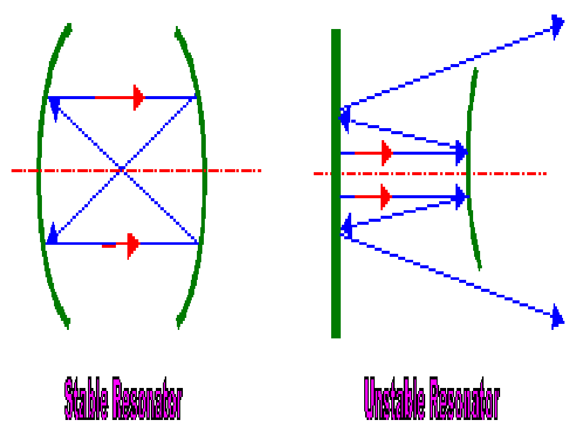

Figure 2.2: Stable and unstable resonators

Resonators can be classified as stable and unstable If a ray entering into the cavity gets reflected many times remains within the cavity, the resonator is said to be **stable**.

On the other hand if a ray entering into the cavity after many reflections walk off the cavity, the resonator is said to be **unstable.**

Equivalent optical wave guide

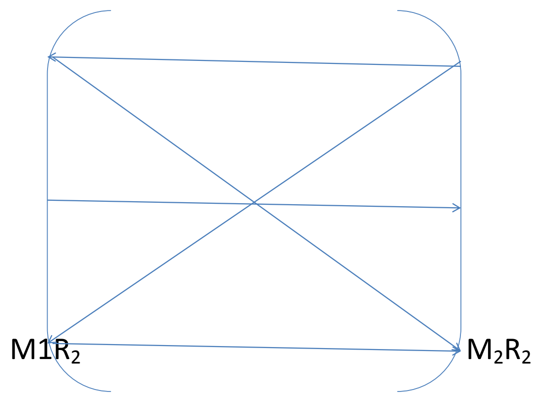

Figure 2.3: Light reflection from spherical mirrors.

To analyze the stability condition, we construct an equivalent optical wave guide consisting of several lenses. This equivalent lens guide will redirect the beam in the same manner as the original spherical mirror cavity. If we follow a ray in the original cavity, Fig 2.3, we first encounter a distance d and then the ray strikes the mirror M_2, gets again reflected and travels in another direction and again reflected at the mirror M_1 and travels certain distance and is reflected at M_2. This cycle repeats over and over again. Infinite sequence of lenses would redirect the beam as the mirror cavity. The infinite sequence of lenses can be regarded as consisting of unit cells of free space, then a lens L_1 another free space and lens L_1.

The combined optical system consisting of an open section of length d followed by a thin lens of focal length f_1 is given by

$$T_{L1} = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f_1} & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & d \\ \frac{-1}{f_1} & 1 - \frac{1}{f_1} \end{pmatrix} \tag{2.2.1}$$

The combined optical system consisting of an open section of length d followed by a thin lens of focal length f_2 is given by

$$T_{L2} = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & d \\ \frac{-1}{f_2} & 1 - \frac{d}{f_2} \end{pmatrix} \tag{2.2.2}$$

Transformation matrix T_m for unit cell is given by

$$T_M = \begin{pmatrix} 1 & d \\ \frac{-1}{f_1} & 1 - \frac{1}{f_1} \end{pmatrix} \begin{pmatrix} 1 & d \\ \frac{-1}{f_2} & 1 - \frac{d}{f_2} \end{pmatrix} \tag{2.2.3}$$

$$= \begin{pmatrix} 1 - \frac{d}{f_2} & d + d(1 - \frac{d}{f_2}) \\ \frac{-1}{f_1} - \frac{1}{f_2}(1 - \frac{d}{f_1}) & (1 - \frac{d}{f_1})(1 - \frac{d}{f_2}) - \frac{d}{f_1} \end{pmatrix} \tag{2.2.4}$$

After N round trips through the resonator, therefore, the initial ray with displacement r_i and slope r'_i is transformed to the ray with displacement r_N and slope r'_N, given by

$$\begin{pmatrix} r_N \\ r'_N \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} r_i \\ r'_i \end{pmatrix} \tag{2.2.5}$$

For three rays $(s+2)^{th}$, $(s+1)^{th}$ and s^{th} , we can write

$$r_{s+2} = Ar_{s+1} + Br'_{s+1}, \tag{2.2.6}$$

$$r'_{s+2} = Cr_{s+1} + Dr'_{s+1}, \tag{2.2.7}$$

$$r_{s+1} = Ar_s + Br'_s, \tag{2.2.8}$$

$$r'_{s+1} = Cr_s + Dr'_s, \tag{2.2.9}$$

where r_{s+2}, r_{s+1} and r_s are vertical distances from the axis and r'_{s+2}, r'_{s+1} and r'_s are slopes.

From eq (2.2.6), we have

$$r'_{s+1} = \frac{r_{s+2}}{B} - \frac{Ar_{s+1}}{B} \tag{2.2.10}$$

Combining eqs (2.2.9) and (2.2.10), we get

$$\frac{r_{s+2}}{B} - \frac{Ar_{s+1}}{B} = Cr_s + Dr'_s \tag{2.2.11}$$

From eq(2.2.8), we have

$$r'_s = \frac{r_{s+1}}{B} - \frac{Ar_s}{B} \tag{2.2.12}$$

Combining eqs (2.2.11) and (2.2.12), we obtain

$$\frac{r_{s+2}}{B} - \frac{Ar_{s+1}}{B} = Cr_s + D(\frac{r_{s+1}}{B} - \frac{Ar_s}{B}) \tag{2.2.13}$$

Multiplying by B and rearranging,we find

$$r_{s+2} - (A+D)r_{s+1} + (AD-BC)r_s = 0 \tag{2.2.14}$$

,

$$AD - BC = 1 \tag{2.2.15}$$

In view of eq (2.2.15), we can rewrite eq (2.2.14) as

$$r_{s+2} - (A+D)r_{s+1} + r_s = 0 \tag{2.2.16}$$

Let the vertical distance r_s be

$$r_s = r_o e^{is\theta} \tag{2.2.17}$$

It the follows that

$$r_{s+1} = r_o e^{i(s+1)\theta} \tag{2.2.18}$$

and

$$r_{s+2} = r_o e^{i(s+2)\theta} \tag{2.2.19}$$

We see from eqs (2.2.17), (2.2.18) and (2.2.19), we find eq (2.2.16) to be

$$r_o e^{is\theta} \lfloor e^{2i\theta} - (A+D)r_o e^{i\theta} + 1 \rfloor = 0 \tag{2.2.20}$$

From this we can write

$$e^{2i\theta} - (A+D)e^{i\theta} + 1 = 0 \tag{2.2.21}$$

Let $e^{i\theta} = y$ eq (2.2.21), then becomes

$$y^2 - (A+D)y + 1 = 0 \tag{2.2.22}$$

The solution of eq (2.2.22) is given by $y = \frac{(A+D)\pm\sqrt{(A+D)^2-4}}{2}$ or

$$y = \frac{A+D}{2} \pm i\sqrt{1 - (\frac{A+D}{2})^2} \tag{2.2.23}$$

Now using $y = e^{i\theta}$, we obtain

$$e^{i\theta} = \frac{A+D}{2} \pm i\sqrt{1 - (\frac{A+D}{2})^2} \tag{2.2.24}$$

$$e^{i\theta} = \cos\theta + i\sin\theta = \frac{A+D}{2} \pm i\sqrt{1 - (\frac{A+D}{2})^2}, \tag{2.2.25}$$

We then see that

$$\cos\theta = \frac{A+D}{2} \tag{2.2.26}$$

,

The rays should be contained with in the mirror. So r_o, r_s, r_{s+1}, r_{s+2} and θ should be real number. Since $cos\theta$ varies from -1 to 1, we can write

$$-1 \leq \frac{A+D}{2} \leq 1 \tag{2.2.27}$$

One can easily verify that

$$0 \leq \frac{A+D+2}{4} \leq 1 \tag{2.2.28}$$

From the unit cell matrix, we have

$$A = 1 - \frac{d}{f_2} \tag{2.2.29}$$

and

$$D = (1 - \frac{d}{f_1})(1 - \frac{d}{f_2}) - \frac{d}{f_1} \tag{2.2.30}$$

Using eqs (2.2.29) and (2.2.30), one can easily show that

$$\frac{A+D+2}{4} = (1 - \frac{d}{2f_1})(1 - \frac{d}{2f_2}) \tag{2.2.31}$$

This stability condition can be described in terms of the radii of the two mirrors and their separation as

$$0 \leq (1 - \frac{d}{R_1})(1 - \frac{d}{R_2}) \leq 1, \tag{2.2.32}$$

where R_1 and R_2 are radii of curvatures of cavity mirrors.

$$0 \leq g_1 g_2 \leq 1 \tag{2.2.33}$$

,

where

$$g_1 = 1 - d/R_1 \tag{2.2.34}$$

and

$$g_2 = 1 - d/R_2 \tag{2.2.35}$$

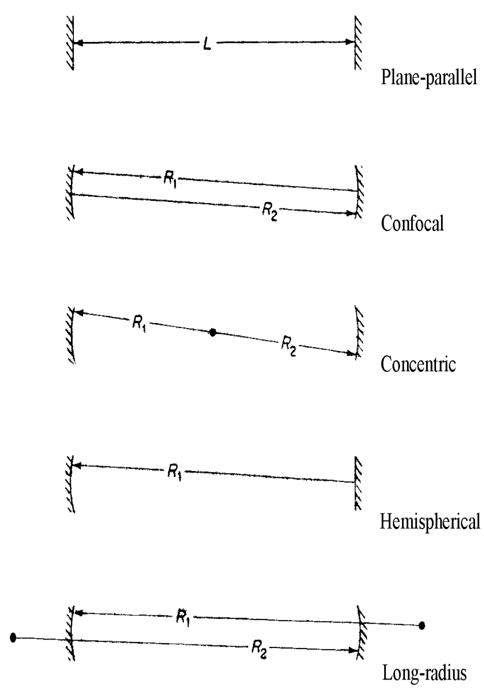

Figure 2.4: Some of typical parameters various stable resonators

Typical parameters for various resonators is shown below;

1) For plane-parallel resonator, $R_1 = R_2 = \infty$ and g_1g_2= 1

2) For spherical resonator (concentric) , $R_1 = R_2 = d/2$, $g_1g_2 = 1$

3) For hemispherical resonator, $R1 = \infty$, $R_2 = d$,$g_1g_2 = 0$

4) For confocal resonator, $R_1 = R_2 = d$, $g_1g_2 = 0$

5) For hemiconfocal resonator ,$R_1 = \infty$, $R_2 = 2d$, $g_1g_2 = \frac{1}{2}$.

These are called the g parameters of the resonator. If the g parameters are such that eq (2.2.33) is satisfied, the resonator is stable. If $g_1g_2 \leq 0$ or $g_1g_2 \geq 1$, however, the resonator is unstable

2.2.2 Characteristics of Laser Light

Laser is simply a source of light but the light has extraordinary properties. Laser radiation is characterized by an extremely high degree of monochromaticity, coherent, directionality and brightness. [5-8]

1) Monochromaticity : Laser light consists of essentially one wavelength, having its origin in stimulated emission from one set of atomic energy levels. The frequency emitted by the laser is given by the difference in energy between the energy levels for which there is radiation emission. This spectral of laser light can be extremel high. It is given by Planck's relationship

$$\upsilon_\nu = \frac{E_2 - E_1}{h} \qquad (2.2.36)$$

where h is the Planck's constant; E_2 is upper level energy; E_1 is lower level energy. The two energy levels between which laser radiation emission occurs are stable. Thus a single frequency is emitted and amplified in the optical cavity. This means that laser radiation has a single wavelength.

2) Coherence: is one of the unique properties of laser light. It arises from the stimulated emission process, which provides the amplification. Since a common stimulus triggers the emission events, which provide the amplified light, the emitted photons are "in step" and have a definite phase relation to each other. This coherence is described in terms of spatial coherence and temporal coherence both of which are important in producing the interference, which is used to produce holograms.

Spatial coherence: It is degree to which a beam of light appears to have originated from a single point in space. Spatial coherence is limited to a given area.

Temporal coherence: It is the extent to which all the photons in a light beam are of the same frequency or wavelength. It is associated with difference in frequencies of two waves. This coherence property is what makes holograms possible. The temporal coherence is limited to a certain time. This comes about because two waves in a laser beam remain coherent for a long time as they move past a given point. The beam coherence time is give by

$$\Delta\tau = \frac{1}{\Delta\nu} \tag{2.2.37}$$

where $\Delta\nu$ is change in frequency. The extremely small values possible for $\Delta\nu$ in laser light make the coherence times of laser light extraordinarily long. The beam coherence length is defined as

$$\Delta\chi = c\Delta\tau \tag{2.2.38}$$

where c is the speed of light. Laser radiation have high spatial and temporal coherence compared with conventional light sources.

3) Directionality: laser emit light that is highly directional. Laser is light emitted as a relatively narrow beam in a specific direction. Ordinary light such as coming from

the sun, a light bulb or candle is emitted in many directions away from the source. Beam divergence θ_d for diffracted limited beam is given by

$$\theta_d = \frac{\beta\lambda}{D} \tag{2.2.39}$$

where λ is wavelength, β is a numerical coefficient of the order of unity and D is the diameter of the beam.

4) Brightness: It is defined as the power emitted per unit surface area per unit solid angle. The units are Watts per square meter per steradian. A steradian is the unit of solid angle. The spectral brightness B of the source is defined as

$$B = \frac{P}{A\Omega} \tag{2.2.40}$$

where P is power of the source, A is cross sectional area and Ω is beam divergence in steradian. $\frac{P}{A} = I_v$ is known as the spectral intensity. Therefore

$$B_v = \frac{I_v}{\Omega} \tag{2.2.41}$$

.

Chapter 3

The Einstein Coefficients and Rate Equation for Two and Three Level Lasers

3.1 The Einstein coefficients

One of the ways an atom can gain energy is to absorb a photon. An atom in the ground state can absorb only certain allowed amounts of energy. For instance, the ground state atom could absorb $E_2 - E_1$ and move to the first excited state or it could absorb $E_3 - E_1$ and move to the second excited state and so on. Where E_1 is energy level 1, E_2 is energy level 2 and E_3 is energy level 3.

During absorption, they must absorb a whole photon because partial absorption is not allowed. That means that the energy of the photon must correspond exactly to the energy difference between two levels of the atom. There are several ways an atom in an excited state can lose its energy.

The energy can be transferred to other atoms, or it can be emitted as light. If it is emitted as light,the wavelength of the emitted light will correspond to the energy lost by the atom. There are mechanisms by which the light can be emitted by spontaneous and stimulated emission.

The processes by which matter emits or absorbs electromagnetic radiation are absorption, spontaneous and stimulated emission. There are three Einstein coefficients associated with any pair of energy levels. Of these three only one is independent. The other two depend upon the coefficient taken to be independent, plus the frequency of the transition and the statistical weights of the two associated terms.

Einstein coefficients are mathematical quantities which are a measure of the probability of absorption or emission of light by an atom or molecule. The Einstein A coefficient is related to the rate of spontaneous emission of light and the Einstein B coefficients are related to the absorption and stimulated emission of light. [5-8]

3.1.1 Einstein coefficient for absorption

By absorbing a photon, an atom in the lower lever makes transition to the upper level.

If N_1 is the population density of the lower level and N_2 is population density of the upper level, the rate of the change of number of atoms in the lower level is proportional to the population density in the lower lever and the spectral density of the incident radiation that an electron in state 1 with energy E_1 will absorb a photon with an energy $hv = E_2 - E_1$ and jump to state 2 with energy E_2. The rate change in the number density of atoms in state 1 per unit time due to absorption will be

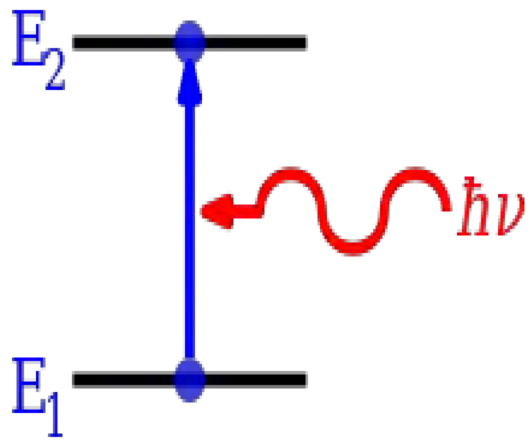

Figure 3.1: Schematic diagram of absorption

$$\frac{dN_1}{dt} = -B_{12}N_1\rho(\upsilon), \tag{3.1.1}$$

where B_{12} is Einstein coefficient for absorption and $\rho(\upsilon)$ is spectral density

3.1.2 Einstein coefficient for emission

Spontaneous emission An atom initially in the excited level 2 with energy E_2, will tend to decay spontaneously to the ground state E_1 releasing a photon of energy $h\nu = E_2 - E_1$ in a random direction. The process is described by the Einstein coefficient A_{21}, with dimension (s^{-1}) , which gives the probability per unit time that an electron in state 2 with energy E_2 will decay spontaneously to state 1 with energy E_1, emitting a photon with an energy $E_2 - E_1 = h\upsilon$.

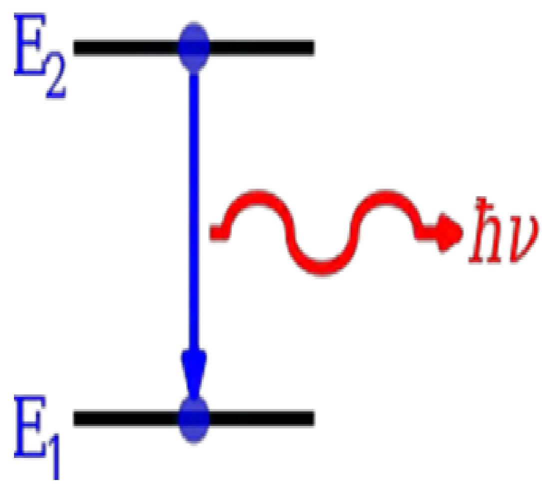

Figure 3.2: Schematic diagram of atomic spontaneous emission

The rate of spontaneous emission depends on the population density in the excited state. If N_1 is the number density of atoms in state 1 then the change in the number density of atoms in state 2 per unit time due to spontaneous emission will be:

$$\frac{dN_2}{dt} = -A_{21}N_2, \tag{3.1.2}$$

The same process results in increasing of the population of the state 1:

$$\frac{dN_1}{dt} = A_{21}N_1, \tag{3.1.3}$$

Stimulated emission; When a photon incident on an atom in an exited state,it stimulated the atom to drop or decay to the lower state E_1. In this process, the atom releases a photon of the same energy, direction and phase as that of the incident photon. The net effect is two identical photon $2h\nu$ in place of one or an increase in the intensity of the incident beam.

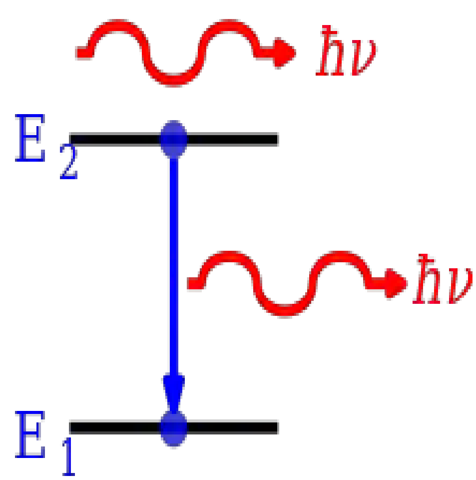

Figure 3.3: Schematic diagram of stimulated emission

It is precisely this process of stimulated emission that makes possible the amplification of light in laser. The process is described by the Einstein coefficient B_{21} $(J^{-1}m^3s^{-2})$, which gives the probability per unit time per unit spectral energy density of the radiation field that an electron in state 2 with energy E_2 will decay to state 1 with energy E_1, emitting a photon with an energy $E_2 - E_1 = h\upsilon$.

The rate of stimulated emission depends on population density in the excited state and spectral density of incident radiation. The change in the number density of atoms in state 1 per unit time due to stimulated emission will be:

$$\frac{dN_1}{dt} = B_{21}N_2\rho(\upsilon) \tag{3.1.4}$$

where $\rho(\upsilon)$ denotes the spectral energy density of the isotropic radiation field at the frequency of the transition.

In a stationary field the total absorption rate $B_{12}N_1\rho(\upsilon)$, which gives the number of photon absorbed per unit volume per second has to be equal the total emission rate $A_{21}N_2 + B_{21}N_2\rho(\upsilon)$ (other wise the spectral energy density $\rho(\upsilon)$ of the radiation field would change). This gives

$$A_{21}N_2 + B_{21}N_2\rho(\upsilon) = B_{12}N_1\rho(\upsilon) \tag{3.1.5}$$

From the Maxwell-Boltzmann distribution , we have, for the number of excited atomic species :

$$\frac{N_2}{N_1} = \frac{g_2}{g_1}e^{\frac{E_1-E_2}{KT}} \tag{3.1.6}$$

whereN_2 and N_1 are the number density of the atomic species excited and ground respectively, k is Boltzmann's constant, T is absolute the temperature, g_2 is the degeneracy of the excited state and g_1 is the degeneracy of the ground state. Solving for $\rho(\upsilon)$ from Eq (3.1.5), we obtain

$$\rho(\upsilon) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2} \tag{3.1.7}$$

or

$$\rho(\upsilon) = \frac{A_{21}}{\frac{B_{12}N_1}{N_2} - B_{21}} \tag{3.1.8}$$

Now substitution of eq (3.1.6) into eq (3.1.8) yields

$$\rho(\upsilon) = \frac{A_{21}}{B_{12}\frac{g_1}{g_2}e^{\frac{E_2-E_1}{KT}} - B_{21}} \tag{3.1.9}$$

We recall from plancks spectral distribution law , we that

$$\rho(\upsilon) = \frac{8\pi\upsilon^2}{c^3}\frac{h\upsilon}{e^{\frac{h\upsilon}{KT}} - 1} \tag{3.1.10}$$

Comparision of eq (3.1.9) with eq (3.1.10), we have

$$\frac{B_{12}g_1}{B_{21}g_2} = 1 \tag{3.1.11}$$

From this one can write

$$B_{12}g_1 = B_{21}g_2 \tag{3.1.12}$$

From eq (3.1.12)

$$B_{12} = \frac{B_{21}g_2}{g_1} \tag{3.1.13}$$

So that, we get (3.1.13)

$$\frac{A_{21}g_2}{B_{12}g_1} = \frac{8\pi h\upsilon^3}{c^3} = \frac{A_{21}}{B_{21}} \tag{3.1.14}$$

When this relation is inserted into the eq (3.1.9), one can also find a relation between A_{21} and B_{12} involving Planck's law. For a simple system with no degeneracy, that is one in which $g_1 = g_2$, we see that $B_{21} = B_{12}$. Thus, the Einstein coefficient for stimulated emission and absorption are equal. If the levels have unequal degeneracy, the probability for absorption is no longer the same as that for stimulated emission.

3.2 Rate equation for a two and three level lasers

3.2.1 Two level laser

Consider a two level system with the upper level 2 and the ground level 1 as shown in Fig 3.4. In order that laser transition may occur, we need a population inversion. Since at normal temperatures, the population of lower level is more than that at the upper level, atoms must be pumped into the upper level by providing them energy equal to the energy difference between the two levels. [5-8]

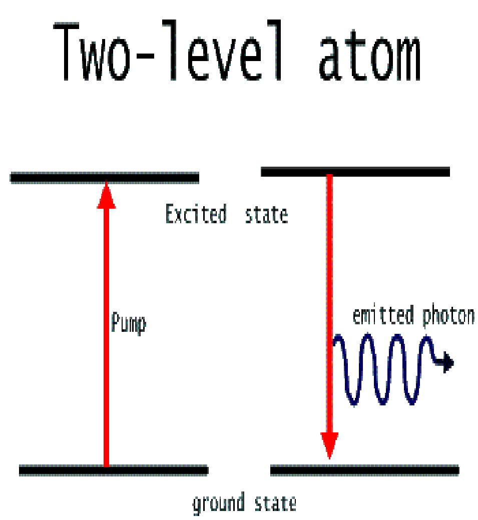

Figure 3.4: Schematic diagram of two level laser

If W_p is the pumping induced transition rate for $1 \to 2$ or $2 \to 1$ and τ is the natural life time of atoms in the upper level, the rate equation for the two levels may be written as follows :

Total population N_t is $N_t = N_2 + N_1$

The difference in population between two level is

$\Delta N = N_1 - N_2$ and $\Delta N + N_t = 2N_1$.

From this we get

$$N_1 = \frac{\Delta N + N_t}{2} \tag{3.2.1}$$

Also, since $N_t - \Delta N = 2N_2$, we get

$$N_2 = \frac{N_t - \Delta N}{2} \tag{3.2.2}$$

The population density N_2 changes in time according to

$$\frac{dN_2}{dt} = -W_{21}(N_2 - N_1) - N_2 A_{21} \tag{3.2.3}$$

$$\frac{dN_2}{dt} = W_{21}(N_1 - N_2) - \frac{N_2}{\tau_{21}} \tag{3.2.4}$$

where $\tau_{21} = \frac{1}{A_{21}}$ is spontaneous emission lifetime, $N_2 W_{21}$ is stimulated emission rate and $N_1 W_{21}$ is absorption rate.

$$\frac{dN_2}{dt} = W_{21}\Delta N - \frac{N_2}{\tau_{21}} \tag{3.2.5}$$

An the steady state eq (3.2.5) reduces to

$$W_{21}\Delta N - \frac{N_2}{\tau_{21}} = 0 \tag{3.2.6}$$

Substituting eq (3.2.2) into (3.2.6)

$$\frac{W_{21}\Delta N \tau_{21} - (\frac{N_t - \Delta N}{2})}{\tau_{21}} = 0 \tag{3.2.7}$$

$$\frac{2W_{21}\Delta N\tau_{21} - N_t + \Delta N}{2\tau_{21}} = 0 \tag{3.2.8}$$

From this one can arrive at

$$\Delta N = \frac{N_t}{1 + 2W_{21}\tau_{21}} \tag{3.2.9}$$

since $W_{21} = \frac{\delta I}{h\nu}$, in which δ is cross section for absorption or stimulated emission and I is intensity, we can write eq (3.2.9)

$$\Delta N = \frac{N_t}{1 + 2\tau_{21}\frac{\delta I}{h\nu}} \tag{3.2.10}$$

Employing the saturation intensity, $I_s = \frac{h\nu}{2\delta\tau_{21}}$, we note that

$$\Delta N = \frac{N_t}{1 + \frac{I}{I_s}} \tag{3.2.11}$$

If $I = I_s$, Eq(3.2.11) reduces to

$$\Delta N = \frac{N_t}{2} \tag{3.2.12}$$

Then,

$$N_1 - N_2 = \frac{N_t}{2} \tag{3.2.13}$$

,

In this saturation absorption, the rate of absorption is equal to the rate of stimulated emission. This is known as **saturation absorption**. When we attempt to achieve continuous laser oscillation using the two level scheme, we encounter a series difficulty. The mechanism we use to excite atoms to level 2 may also de-excite them. For instance, if we try to pump atoms from level 1 to 2 by irradiating the medium. The radiation will induce both upward transitions $1 \rightarrow 2$ (absorption) and downward transition $2 \rightarrow 1$, (stimulated emission).

The best we can do by this precess of continuous wave optical pumping is to produce the same number of atoms in level 2 as in level 1 by saturating the $1 \rightarrow 2$

transition. We can not obtain a positive steady state population inversion using only two atomic level in the pumping process. One resolution of this difficulty is to make use of a three level laser.

3.2.2 Three level laser

In the previous section we saw that one cannot create steady population inversion between two level just by using pumping between these level. Thus in order to produce a steady state population inversion, one makes use of three level system.

We consider a three level system consisting of energy levels E_1, E_2 and E_3 all of which are assumed to be non-degenerate. Let us consider three level system with population densities N_1, N_2 and N_3 in the ground level, with mate-stable level and excited level is respectively Fig 3.5. The pump is assumed to lift atoms from level 1 to level 3 from which they decay rapidly to level 2 through some non-radiative process. This effectively transfers atoms from the ground level 1 to the excited level 2 which is now the upper laser level, the lower laser level being the ground state 1

If the radiative relaxation from level 3 to level 2 is very fast then the atoms will relax down to level 2 rather than to level 1. Since the upper level 3 is not at laser level, it can be a broad level so that a broad band light source may be efficiently used as a pump source. [5-8]

The total population is

$$N_t = N_1 + N_2 + N_3 \tag{3.2.14}$$

Due to the fact that the lifetime in the state E_2 is much longer than that in the state E_3, it is possible to create population inversion between the state E_2 and E_1 ($E_2 > E_1$) by pumping the system from E_1 to E_3.

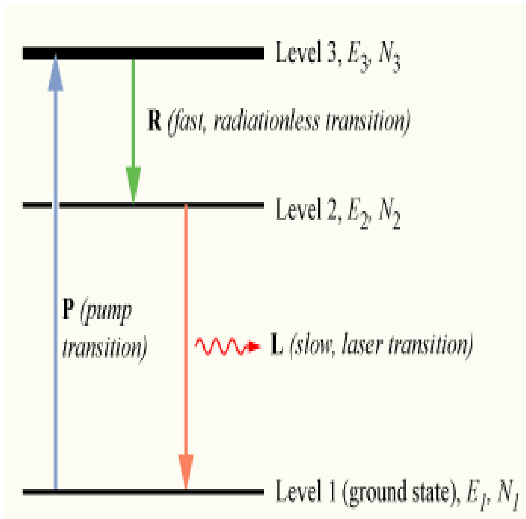

Figure 3.5: Schematic diagram of three level laser

The rate of change of population density in level 3 is

$$\frac{dN_3}{dt} = W_p(N_1 - N_3) - N_3\tau_{32}, \tag{3.2.15}$$

where W_p is pumping rate going up and τ_{32} is total transition probability from level 3 to level 2 and can be written as

$$\tau_{32} = A_{32} + S_{32} \tag{3.2.16}$$

where A_{32} and S_{32} correspond respectively to radiative and non radiative transition rate between level 3 and 2. The rate of the change of population density in the level 2 is given by

$$\frac{dN_2}{dt} = W_1(N_1 - N_2)N_3\tau_{32} - N_2\tau_{21}, \tag{3.2.17}$$

where W_1 is pumping rate of level 1. The rate equation for the ground state is obtained from the above two equations by number conservation. That is,

$$\frac{dN_1}{dt} = W_p(N_1 - N_3) + W_1(N_1 - N_2) - N_2\tau_{21} \tag{3.2.18}$$

At the steady state,

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0 \tag{3.2.19}$$

Thus,at steady state eqs (3.2.15), (3.2.17) and (3.2.18)

$$0 = W_p(N_1 - N_3) - N_3\tau_{32} \tag{3.2.20}$$

$$0 = W_1(N_1 - N_2) + N_3\tau_{32} - N_2\tau_{21} \tag{3.2.21}$$

$$0 = W_p(N_1 - N_3) + W_1(N_1 - N_2) - N_2\tau_{21} \tag{3.2.22}$$

From eq (3.2.20)

$$W_p(N_1 - N_3) = N_3\tau_{32} \tag{3.2.23}$$

From which one can write

$$\frac{N_3}{N_1} = \frac{W_p}{W_p + \tau_{32}} \tag{3.2.24}$$

From eq (3.2.21), one can write

$$W_1N_1 + N_3\tau_{32} = (\tau_{21} + W_1)N_2 \tag{3.2.25}$$

Since $N_3 = \frac{W_pN_1}{W_p+\tau_{32}}$ substituting this Equation into eqs (3.2.24), we get

$$W_1N_1 + \frac{W_pN_1}{W_p + \tau_{32}}\tau_{32} = (\tau_{21} + W_1)N_2 \tag{3.2.26}$$

From this equation one can write

$$\frac{N_2}{N_1} = \frac{W_1(W_p + \tau_{32}) + \tau_{32}W_p}{(W_1 + \tau_{21})(W_p + \tau_{32})} \tag{3.2.27}$$

Subtracting 1 from both side of this equation, we get

$$\frac{N_2 - N_1}{N_1} = \frac{W_1(W_p + \tau_{32}) + \tau_{32}W_p}{(W_1 + \tau_{21})(W_p + \tau_{32})} - 1 \tag{3.2.28}$$

From which follows

$$\frac{N_2 - N_1}{N_1} = \frac{W_p(\tau_{32} - \tau_{21}) - \tau_{32}\tau_{21}}{(W_1 + \tau_{21})(W_p + \tau_{32})} \tag{3.2.29}$$

We know that $N = N_1 + N_2 + N_3$

From eqs (3.2.24) and (3.2.27), we can write N_3 and N_2 in terms of N_1

$$N_1 + \frac{W_pN_1}{W_p + \tau_{32}} + \frac{W_1(W_p + \tau_{32})N_1 + \tau_{32}W_pN_1}{(W_1 + \tau_{21})(W_p + \tau_{32})} = N \tag{3.2.30}$$

$$N_1(1 + \frac{W_p}{W_p + \tau_{32}} + \frac{W_1(W_p + \tau_{32}) + \tau_{32}W_p}{(W_1 + \tau_{21})(W_p + \tau_{32})}) = N \tag{3.2.31}$$

solving for N_1 from this equation ,we get

$$N_1 = \frac{N(W_1 + \tau_{21})(W_p + \tau_{32})}{(W_1 + \tau_{21})(W_p + \tau_{32}) + W_p(W_1 + \tau_{21}) + W_1(W_p + \tau_{32}) + \tau_{32}W_1} \tag{3.2.32}$$

substituting into eq(3.2.32), we have

$$\frac{N_2 - N_1}{N_1} = \frac{W_p(\tau_{32} - \tau_{21}) - \tau_{32}\tau_{21}}{3W_1W_p + 2W_1\tau_{32} + 2W_p\tau_{21} + \tau_{21}\tau_{32} + T_{32}W_p} \tag{3.2.33}$$

From the above equation, one may see that in order to obtain population inversion between level 2 and 1, i.e., for $N_2 - N_1$ to be positive a necessary condition is that

$$\tau_{32} > \tau_{21}, \tag{3.2.34}$$

since the lifetime of level 3 and 2 are proportional to the relaxation rate according eq(3.2.34), the lifetime of level 3 must be smaller than that of level 2 for attainment of population inversion between 1 and 2. If this condition is satisfied then according to eq (3.2.33) there is a minimum pumping rate required to achieve population which is given by

$$0 = \frac{W_p(\tau_{32} - \tau_{21}) - \tau_{32}\tau_{21}}{3W_1W_p + 2W_1\tau_{32} + 2W_p\tau_{21} + \tau_{21}\tau_{32} + \tau_{32}W_p} \tag{3.2.35}$$

then

$$W_p(\tau_{32} - \tau_{21}) - \tau_{32}\tau_{21} = 0 \tag{3.2.36}$$

or

$$W_p = \frac{\tau_{32}\tau_{21}}{\tau_{32} - \tau_{21}} \tag{3.2.37}$$

This equation is the minimum pump rate required to operate three level system.

Chapter 4

Types and Application of Lasers

4.1 Types of Laser

Laser are often classified according to the method used to obtain a population inversion and gain. These are solid state lasers, gas lasers, liquid lasers, chemical lasers and semiconductor lasers, etc. In this chapter, the most important types of lasers are considered in some detail.

It should be pointed out that there are many more lasers in existence than just those described here. This chapter therefore, concentrates on those types that are most commonly used and whose characteristics are representative of a category of lasers. [5-12]

4.1.1 Solid state laser

Solid state lasers use high density solid media as active laser materials. Ions are introduced as an impurity into host materials, which can be crystalline or glass. Semiconductors are excluded since their energy levels are quite different.

Ions of transition elements, particularly rare earth elements Neodymium (Nd), Ytterbium(Yb), Erbium (Er), Holmium(Ho) etc.) or transition metals Chromium(Cr), Titanium(Ti) etc.) are used most commonly as dopants. Host materials include crystals like sapphire Al_2O_3, YLF ($YLiF_4$), YAG ($Y_3Al_5O_{12}$), LISAF ($LiSrAlF_6$), LICAF ($LiCaAlF_6$), as well as glasses from silicate (SiO_2) and phosphate (P_2O_5).

They are typically electric dipole forbidden, so they have very long lifetimes. Glasses are easier to fabricate, but crystals have better thermal properties. The solid state materials can be ruby, neodymium-yttrium aluminum garnet etc.

Ruby laser

This type of laser is the first to be made to operate and still continuous to be used. Ruby, which has been known for hundreds of years as a naturally occurring precious stone, is a crystal consisting of the naturally formed of crystal of aluminum oxide (Al_2O_3) called corundum,in which some of the Al^{3+} ions are replaced by chromium (Cr^{3+}) ions.

As a laser material,it is usually obtained by crystal growth from a molten mixture of (Al_2O_3) with a small percentage of (Cr_2O_3) (0.05 percentage by weight). Without the addition of (Cr_2O_3) the crystal that forms is colorless and it only needs the small addition of (Cr_2O_3) to make the crystal appear a pink color due to the green and violet absorption bands of Cr^{3+} ions. Ruby laser is a three level laser. It is pumped with a xenon flash lamp. When the Cr^{3+} in a ruby crystal absorb photons of visible light at 550nm, some electrons jumped from their ground state to the excited state. The electrons excited to these state almost immediately dissipate their excess energy to the surrounding crystal lattice. As a result of the radiation-less transitions, the electrons jump to one of the two closely spaced meta-stable states. Stimulated emission occurs on the $EtoE_0$ transition,generating light at a wavelength 694.3nm. Ruby laser find wide application in holography, plasma diagnostics and dermatology.

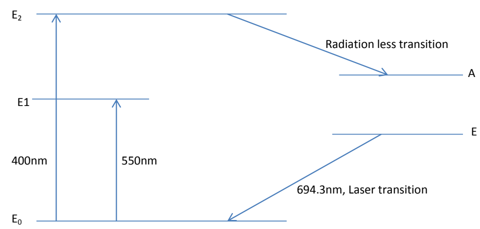

Figure 4.1: Electronic transition in ruby laser

Neodymium Yttrium-Aluminium-Garnet (Nd:YAG)

Neodymium YAG consists of Yttrium-Aluminium-Garnet(YAG) $Y_3Al_5O_{12}$ in which some of the Y^{3+} ions are replaced by Nd^{3+} ions. Neodymium is a rare earth element, where the active electronic states are shielded inner 4f states. Nd:YAG is a four level laser, the main emission of Nd:YAG is at $1.064\mu m$. Another line with considerable less gain is at $1.32\mu m$. Initially Nd:YAG was flashlamp pumped. Today, much more efficient pumping is possible with laser diodes and diode arrays.

Diode pumped versions which can be very compact and efficient become a competition for the CO_2 laser in material processing, range finding, surgery, pumping of other lasers in combination with frequency doubling to produce a green 532nm beam. Neodymium can also be doped in a host of other crystals such as (Nd:YLF) emitting at 1047μm,(Nd:YVO) emitting at 1.064μm, glass (Nd: Glass) at 1.062μm,(Silicate glasses), 1.054μm (Phosphate glasses).Glass lasers have been used to build extremely high power (Tera-watt), high energy (Mega joules) multiple beam systems for inertial confinement fusion.

The big advantage of glass is that it can be fabricated on meter scale which is hard or even impossible to do with crystalline materials. Other rare earth elements are Er^{3+}, Tm^{3+}, Ho^{3+}, Er^{3+}, which have emission lines at 1.53μm and in the $2-3\lambda m$ range.

Ytterbium :Yttrium-Aluminium-Garnet (Yb:YAG)

Ytterbium YAG is a three level laser, emitting at 1.030μm. The lower laser level is only 500-600cm^{-1} (60meV) above the ground state and is therefore at room temperature heavily thermally populated. The laser is pumped at 941 or 968 nm with laser diodes to provide the high brightness pumping needed to achieve gain. However, Yb:YAG has many advantages over other laser materials: Very low quantum defect ,i.e, difference between the photon energy necessary for pumping and photon energy of the emitted radiation, long radiative lifetime of the upper laser level.

4.1.2 Gas laser

Laser action is possible in a wide variety of gases. The basic requirements are gain and feed back, a suitable excitation mechanism, a gas that can be excited to produce a population inversion, a tube to contain the laser gas and an optical resonator to generate the beam.

The physics of atoms and molecules in the gaseous state was well understood by the mid 1950's, when the laser concept was developed. The first proposal for making lasers envisioned using a gas as the active medium.

The active medium in a gas laser is a gas sealed in a tube to isolate it from enviroment.The gas may be a single pure gas such as Helium and Neon. The family of rare gases such as Helium, Neon, Argon, Krypton and Xenon are the most common elements used in gas laser. The names used for lasers identify the active elements in the gas. In the helium-neon laser, two elements are active.He collects energy from the electronic discharge and transfers it to the neon atoms or chromium ion that emit the laser light. Gas lasers are usually excited by electrical means, that means, pumping is achieved by passing a sufficiently large current through the gas. We discuss here the most representative gas lasers including the Helium-Neon Laser, Argon and Krypton ion lasers, Carbon laser and Excimer lasers.

Helium-Neon laser

Helium-Neon laser is the most important noble gas laser. He atoms are used for collision excitation of Ne. Laser transitions result from electronic states of Ne. Mixture ratio is typically 5:1. Main lasing wavelength is 633 nm. Other wavelengths $(543.5nm, 593.9nm, 611.8nm, 1.1523\mu m, 1.52\mu m, 3.3913\mu m)$. Pumping is achieved by a longitudinal(electrical) discharge, The helium is excited by electron impact. The energy is then transferred to Neon by collisions.

The first He-Ne laser operated at the $1.1523\mu m$ line [8].He-Ne lasers are used in many applications such as alignment Interferometry, spectroscopy, bar-code scanning, metrology medical diagnosis and optical demonstrations because of their good beam coherence and quality.

Argon and Krypton ion lasers

Similar to the He-Ne-laser the Argon ion gas laser is pumped by electric discharge and emits light at wavelength:488.0nm, 514.5nm, 351nm, 465.8nm, 472.7nm and 528.7nm. The ground state in this case is singly ionized Argon ion.

This laser is a four-level device in which argon ions are formed by an electrical or radio-frequency discharge. The ions are then excited to obtain population inversion. Main lasing wavelength is 515 nm (blue).Required ion temperature is very high (3000K),hence water cooling is necessary.

Argon-ion lasers are widely used in ophthalmology to treat diabetic retinopathy,lithography and pumping of other lasers. The Krypton ion gas laser is analogous to the Argon gas laser with wavelength: 416nm,530.9nm, 568.2nm, 647.1nm, 676.4nm, 752.5nm and 799.3nm.

Carbon laser

Carbon dioxide gas laser is one of the most powerful lasers. The standard output of these lasers is at 10.6 mm, and output power can range from less than 1W to more than 10 kW . In the carbon dioxide (CO_2) gas laser the laser transitions are related to vibrational-rotational excitations. Lasing action results from transitions between vibrational levels of (CO_2). N_2 and He are also added for collision excitation. (CO_2) lasers are highly efficient approaching 30 percent . The main emission wavelengths are $10.6\mu m$ and $9.4\mu m$. They are pumped by transverse (high power) or longitudinal (low power) electrical discharge. It is heavily used in the material processing industry for cutting, drilling marking and welding of steel materials processing and in various medical application such as dermatology and in the medical area for surgery and tool producing clean cuts with little bleeding.

Carbon monoxide (CO) gas laser: Wavelength $2.6-4\mu m$, $4.8-8.3\mu m$ pumped by electrical discharge. Also used in material processing such as engraving and welding and in photo-acoustic spectroscopy. Output powers as high as 100kW have been demonstrated.

4.1.3 Excimer lasers

Excimer lasers (the name came from excited and dimers) use reactive gases like Chlorine and Fluorine mixed with noble gases like Argon or Krypton or Xenon. This lasers produce light in the ultraviolet range. Chemical lasers emitting in the UV: 193nm Argon-Fluorine(Ar-F), 248nm Krypton-Fluorine(Kr-F),308nm Xenon-Chlorine(Xe-Cl) and 353nm Xenon-Fluorine(Xe-F.

These are molecules that exist only if one of the atoms is electronically excited. Without excitation the two atoms repell each other. Thus the electronic ground state is not stable and is therefore not populated, which is ideal for laser operation. These lasers are used for ultraviolet lithography in the semiconductor industry and laser surgery.

4.1.4 Dye or Liquid lasers

Dye lasers use organic materials that generally emit in the visible spectrum and are thus colored. These molecules are diluted in a solvent (usually an alcohol, like ethylene glycol or methanol).

The pump source of dye lasers is optical: either an arc lamp or, in the majority of cases, another laser (gas or solid state).

The whole of the visible spectrum is covered. In fact, the dyes are complex organic molecules that have many energy levels. The levels are so close together that they are considered as an energy band. In general, a molecule of dye covers continuously a region of about fifty nanometers in the visible.

Dye lasers are the only ones to cover the visible spectrum entirely. Despite these interesting properties, dye lasers are little used because their implementation is impractical: to prevent the molecules from being destroyed by the pump source, the dye circulates in the pumping zone from a reservoir. In addition, the dye and solvent mixture degrades with time and must be changed regularly.

When the solution of dye molecules is optically excited by a wavelength of radiation with good absorption coefficient, it emits radiation of longer wavelength, known as fluorescence. The energy difference between absorbed and emitted photons is mostly used by non- radiative transitions and creates heat in the system.

Organic dye lasers, as tunable and coherent light sources, are becoming increasingly important in spectroscopy, holography, and in biomedical applications.

These dyes can be excited optically with Argon lasers for example and emit at 390-435nm (stilbene), 460-515nm (coumarin 102), 570-640 nm (rhodamine 6G) and many others. These lasers have been widely used in research and spectroscopy because of their wide tuning ranges. Un-fortunately, dyes are carcinogenic and as soon as tunable solid state laser media became available dye laser became extinct. Due to the large wavelength range, dye lasers are used in many scientific spectroscopic applications. They are also used in medicine for retinopathy and curing dermatological diseases.

4.1.5 Chemical lasers

A chemical laser is a laser that obtains its energy from a chemical reaction. Examples of chemical lasers are the chemical oxygen iodine laser (COIL), all gas-phase iodine laser (AGIL), Hydrogen fluoride laser and,deuterium fluoride laser etc.

4.1.6 Semiconductor laser

Semiconductor lasers are one of the most important laser types to day. In these lasers, junction diodes are used. The semiconductor is doped by both the acceptors and donors. These are known as injection laser diodes. They can be used directly in applications, as well as to pump solid state lasers. To work as laser active media, semiconductors must have a direct band-gap (so, elements like Silicon(Si) and Germanium(Ge)would not work).

Emission wavelengths are in the range 630 - 1600 nm. Majority of semiconductor laser use compounds of group III-V elements (Aluminum (Al), Gallium(Ga), Indium(In), Nitrogen (N), Phosphorus(P), Arsenic(As), Antimony (Sb). Other compounds are rare but possible. group II-IV compounds yield shorter and group IV-VI wavelength yield longer wavelengths.

The Aluminum-Gallium-Arsenic (AlGaAs) based lasers in the wavelength range 670nm-780 nm are used in compact disc players and therefore are the most common and cheapest lasers in the world.

The largest applications of semiconductor lasers are in communication, in which the laser provides the signal, and in compact disk players, in which the laser is focused into the disk grooves and reflected to detect the digitally coded information. They are also used in high-speed printing systems and laser pointers and as pump sources for solid-state lasers (mainly Nd:YAG)

Applications depending on active region, telecommunications, holography, printing, weapons, machining, welding, pump sources for other lasers, high beam headlights for automobiles.[7]

4.2 Application of lasers

Many scientific, military, medical and commercial laser applications have been developed since the invention of the laser in 1958. The coherency, high monochromaticity, and ability to reach extremely high powers are all properties which allow for these specialized applications. These are the many types of Application of Laser available for difference purposes. Depending up on the sources they can be described as below. [5-12]

4.2.1 Scientific application

In science, lasers are used in many ways, including: a wide variety of interferometric techniques, Raman spectroscopy, Laser induced breakdown spectroscopy, Atmospheric,investigating nonlinear optics phenomena,Holographic techniques employing lasers also contribute to a number of measurement techniques,Laser based lidar (Light radar) technology has application in geology, seismology, remote sensing and atmospheric physics, Lasers have been used aboard spacecraft such as in the Cassini-Huygens mission.

In astronomy, lasers have been used to create artificial laser guide stars, used as reference objects for adaptive optics telescopes. Lasers may also be indirectly used in spectroscopy as a micro-sampling system, a technique termed Laser ablation (LA), which is typically applied to ICP-MS apparatus resulting in the powerful LA- ICP-MS. The principles of laser spectroscopy are discussed by Demtrfider[2] and the use of tunable lasers in spectroscopy are described in Tunable Laser Applications.[3] .

Surveying and ranging laser

Helium-neon and semiconductor laser have become standard part of the field surveyiors equipment. A fast laser pulse is sent to a corner reflector at the point to be measured to get distance. When the Apollo 11 and 14 astronauts put corner reflectors on the surface of the moon for determination of the earth moon distance. A power laser pulse from the MacDonald observatory in Texas had spread to about 3km radius by the time it got to the moon, but the reflection was strong enough to be detected. We now know the range from the moon to Texas within about 15cm, a nine significant digit measurement. A pulsed ruby laser was used for this measurement. [9-10]

Photochemistry

Some laser systems, through the process of mode locking, can produce extremely brief pulses of light - as short as picoseconds or femto seconds(10^{-12} - 10^{-15})seconds. Such pulses can be used to initiate and analyses chemical reactions, a technique known as photochemistry. The short pulses can be used to probe the process of the reaction at a very high temporal resolution, allowing the detection of short-lived intermediate molecules. This method is particularly useful in biochemistry, where it is used to analys details of protein folding and function. [10]

Laser bar-code scanners

Supermarket scanners typically use helium-neon lasers to scan the universal bar-codes to identify products. The laser beam bounces off a rotating mirror and scans the code, sending a modulated beam to a light detector and then to a computer which has the product information stored. Semiconductor lasers can also be used for this purpose. laser bar code scanners for industrial use, micro scan offers a wide range of quality products to read linear bar-codes and stacked symbols, with features such as high speed reading, wide field of view, symbol reconstruction, and aggressive decoding technology.

Displays Laser

projection displays containing RGB sources can be used for cinemas, home videos, flight simulators, etc., and are often superior to other displays concerning possible screen dimensions, resolution and color saturation. However, further reductions in manufacturing costs will be essential for deep market penetration.

Data Storage

Optical data storage e.g. in compact disks (CDs), DVDs, Blu-ray Discs and magneto-optical disks, nearly always relies on a laser source, which has a high spatial coherence and can thus be used to address very tiny spots in the recording medium, allowing a very high density data storage. Another case is holography, where the temporal coherence can also be important

Laser/cooling

A technique that has recent success is laser cooling. This involves atom trapping, a method where a number of atoms are confined in a specially shaped arrangement of electric and magnetic fields. Shining particular wavelengths of laser light at the ions or atoms slows them down, thus cooling them. As this process is continued, they all are slowed and have the same energy level, forming an unusual arrangement of matter known as a Boses-Einstein condensate.

Nuclear fusion

Some of the world's most powerful and complex arrangements of multiple lasers and optical amplifiers are used to produce extremely high intensity pulses of light of extremely short duration. These pulses are arranged such that they impact pellets of tritium-deuterium simultaneously from all directions, hoping that the squeezing effect of the impacts will induce atomic fusion in the pellets.This technique, known as "inertial confinement fusion", so far has not been able to achieve "break even", that is, so far the fusion reaction generates less power than is used to power the lasers, but research continues.

Microscopy

Confocal laser scanning microscopy and two-photon excitation microscopy make use of lasers to obtain blur-free images of thick specimens at various depths. Laser capture micro dissection use lasers to procure specific cell populations from a tissue section under microscopic visualization. Additional laser microscopy techniques include harmonic microscopy, four-wave mixing microscopy and interferometric microscopy.

4.2.2 Military applications

There are a variety of military laser applications. In relatively few cases, lasers are used as weapons; the "lasers word" has become popular in movies, but not in practice. Some high-power lasers are currently developed for potential use as directed energy weapons on the battle field, or for destroying missiles, projectiles and mines.

In other cases, lasers function as target designators or laser sights (essentially laser pointers emitting visible or invisible laser beams),or as irritating or blinding (normally not directly destroying) countermeasures e.g.against heat-seeking anti-aircraft missiles. It is also possible to blind soldiers temporarily or permanently with laser beams,although the latter is forbidden by rules of war. There are also many laser applications which are not specific for military use, e.g. in areas such as range finding, lidar, and optical communications.[5-8]

4.2.3 Lasers medicine applications

There is a wide range of medical applications. Often these relate to the outer parts of the human body, which are easily reached with light; examples are eye surgery and vision correction,dentistry, dermatology (e.g. photodynamic therapy of cancer), and various kinds of cosmetic treatment such as tattoo removal and hair removal.

Lasers are also used for surgery (e.g. of the prostate), exploiting the possibility to cut tissues while causing minimal bleeding. Some operations can be done with endoscopic means; an endoscope may contain an optical fiber for delivering light light to the operation scene and another fiber for imaging, apart from additional channels for mechanical instruments.Very different types of lasers are required for medical applications, depending on the optical wavelength,output power,pulse format, etc.

In many cases, the laser wavelength is chosen such that certain substances (e.g. pigments in tattoos or caries in teeth) absorb light more strongly than surrounding tissue, so that they can be more precisely targeted. Medical lasers are not always used for therapy. Some of them rather assist the diagnosis, e.g. via methods of ocular imaging, laser microscopy or spectroscopy. Laser types used in dermatology include ruby(694 nm), alexandrite (755 nm), pulsed diode array (810 nm), Nd:YAG (1064 nm), Ho:YAG (2090 nm), and Er:YAG (2940 nm.

4.2.4 Industrial and commercial application

Lasers are widely used in manufacturing, e.g. for cutting, drilling, welding, cladding, soldering (brazing), hardening, ablating, surface treatment, marking, engraving, micromachining, pulsed laser deposition, lithography, alignment, etc. In most cases, relatively high optical intensities are applied to a small spot, leading to intense heating, possibly evaporation and plasma generation. Essential aspects are the high spatial coherence of laser light, allowing for strong focusing, and often also the potential for generating intense pulses.

Laser processing methods have many advantages, compared with mechanical approaches. They allow the fabrication of very fine structures with high quality, avoiding mechanical stress such as caused by mechanical drills and blades. A laser beam with high beam quality can be used to drill very fine and deep holes, e.g. for injection nozzles. A high processing speed is often achieved, e.g. in the fabrication of filter sieves. Further, the lifetime limitation of mechanical tools is removed. It can also be advantageous to process materials without touching them.

The requirements on optical power and beam quality depend very much on the application and the involved materials. For example, laser marking on plastics can be done with fairly low power levels, whereas cutting, welding or drilling on metals requires much more - often multiple kilowatts. Soldering applications may require a high power but only a moderate beam quality, whereas particularly remote welding (i.e., welding with a substantial distance between laser head and welded parts) depends on a high beam quality.

Laser-aided manufacturing often allows one to produce the essentially same parts with higher quality and/or lower cost. Also, it is often possible to realize entirely new part designs or the use of new materials. For example, automobile parts are increasingly made of light materials such as aluminum, which require tentatively more laser joining operations. Weight reductions are possible not only by the user of lighter materials, but also e.g. by producing them with shorter flanges due to higher precision than is feasible with conventional production methods

Lasers in Communication

Optical communication has been one of the driving forces in developing laser diode technology. Today, diode lasers are the key components of any broadband communication systems. They are employed as high speed transmitter in digital and analog fiber optic networks, to pump lasers in Erbium doped amplifiers or as high-power pulsed lasers in test and measurement field.

Digital data transmission

Digital data transmission is an important part of modern society. Optical communication is any form of telecommunication that uses light as the transmission medium. An optical communication system consists of a transmitter, which encodes a message into an optical signal, a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal.

Radio-Frequency-over-fiber

Refers to transmission of analog multiplexed radio-frequency signals over an optical fiber medium. RF-over-fiber technology delivers unprecedented performance levels for a broad range of applications from wireless networks to high-frequency signal distribution in military.

Optical time domain reflectometry (OTDR)

is a fast spreading test method for checking condition of fiber optic cablings As the fiber optic networks are built closer and closer to end users the cablings are laid in increasingly demanding environment requiring easy and simple diagnostics. In Optical time domain reflectometry high power laser pulses are shot out to fiber cabling and the condition of the fiber link can be determined form the back reflection of the pulses.

Welding and Cutting

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for welding and cutting. The automobile industry makes extensive use of carbon dioxide lasers with powers up to several kilowatts for computer controlled welding on auto assembly lines.

Gamier points out an interesting application of CO_2 lasers to the welding of stainless steel handles on copper cooking pots. A nearly impossible task for conventional welding because of the great difference in thermal conductivities between stainless steel and copper.It is done so quickly by the laser that the thermal conductivities are irrelevant.

Metrology Lasers

These are widely used in optical metrology,e.g.for extremely precise position measurements and optical surface profiling with interferometers,for long-distance range finding and navigation.Laser scanners are based on collimated laser beams, which can read e.g. bar codes or other graphics over some distance.It is also possible to scan three-dimensional objects,e.g.in the context of crime scene investigation. Optical sampling is a technique applied for the characterization of fast electronic micro-circuits, microwave photonics, tera-hertz science, etc. Lasers also allow for extremely precise time measurements and are therefore essential component of optical clocks which are beginning to outperform the currently used cesium atomic clocks. Fiber-optic sensors, often probed with laser light, allow for the distributed measurement of temperature, stress, and other quantities e.g. in oil pipelines and wings of airplanes.

Spectroscopy Laser

spectroscopy is used in many different forms and in a wide range of applications. For example, atmospheric physics and pollution monitoring profits from trace gas sensing with differential absorption lidar technology. Solid materials can be analyzed with laser-induced breakdown spectroscopy. Laser spectroscopy also plays a role in medicine (e.g. cancer detection), biology, and various types of fundamental research, partly related to metrology.

Chapter 5

Pulsed and Continues Wave Lasers

MODES OF OPERATION :The output of a laser may be a continuous constant-amplitude output (known as continuous wave); or pulsed, by using the techniques of Q-switching, mode locking, or gain-switching.

In pulsed operation,much higher peak powers can be achieved. Some types of lasers, such as dye lasers and vibronic solid-state lasers can produce light over a broad range of wavelengths; this property makes them suitable for generating extremely short pulses of light, on the order of a few femtoseconds.[5-8]

5.1 Continuous wave operation

In the continuous wave (CW) mode of operation, the output of a laser is relatively constant with respect to time. The population inversion required for lasing is continually maintained by a steady pump source. Continuous-wave (cw) operation of a laser means that the laser is continuously pumped and continuously emits light.

The emission can occur in a single resonator mode(single-frequency operation) or on multiple modes. The first continuous-wave laser was a helium-neon laser operating at 1153 nm,a version working with the now common emission wavelength of 632.8 nm was demonstrated soon after that,Later on,many other types of lasers were developed which can also be operated continuously: other gas lasers,many types of solid-state lasers (including semiconductor lasers),and dye lasers.

In continuous-wave operation, some lasers exhibit too strong heating of the gain medium. The heating can then be reduced by quasi-continuous-wave operation, where the pump power is only switched on for limited time intervals. Continuous-wave Mode Locking;Some lasers are called continuous-wave mode-locked. This means that the laser is mode-locked, and the pulse energy (or average power) is constant, i.e. there is no Q-switched mode locking.

Despite the emission of pulses, mode locking can be considered as a kind of continuous-wave operation in the sense that the resonator modes are excited with constant powers.In most higher-power systems, one is able to adjust the power.In low power gas lasers, such as He-Ne, the power level is fixed by design and performance usually degrades with long term use.

5.2 Pulsed operation

In the pulsed mode of operation, the output of a laser varies with respect to time, typically taking the form of alternating 'on' and 'off' periods.In many applications one aims to deposit as much energy as possible at a given place in as short time as possible.

In laser ablation for example, a small volume of material at the surface of a work piece might evaporate if it gets the energy required to heat it up far enough in very short time. If, however, the same energy is spread over a longer time, the heat may have time to disperse into the bulk of the piece, and less material evaporates. There are a number of methods to achieve this.

Pulsed lasers : have very high intensities because the laser intensity is concentrated in a very short time duration. A Q-switched laser is a pulsed laser which contains a shutter-like device that does not allow emission of laser light until opened. Energy is built-up in a Q-switched laser and released by opening the device to produce a single, intense laser pulse.

Pulsed pumping :Another method of achieving pulsed laser operation is to pump the laser material with a source that is itself pulsed, either through electronic charging in the case of flashlamps, or another laser which is already pulsed.Pulsed pumping was historically used with dye lasers where the inverted population lifetime of a dye molecule was so short that a high energy,fast pump was needed.

The way to overcome this problem was to charge up large capacitors which are then switched to discharge through flashlamps, producing a broad spectrum pump flash. Pulsed pumping is also required for lasers which disrupt the gain medium so much during the laser process that lasing has to cease for a short period. These lasers, such as the excimer laser and the copper vapour laser, can never be operated in CW mode.13

5.3 Q-switching

In a Q-switched laser, the population inversion (usually produced in the same way as Continuous wave operation) is allowed to build up by making the cavity conditions (the 'Q') unfavorable for lasing. Then, when the pump energy stored in the laser medium is at the desired level, the 'Q' is adjusted (electro- or acousto-optically) to favourable conditions, releasing the pulse. This results in high peak powers as the average power of the laser (were it running in Continuous wave mode) is packed into a shorter time frame.

The Q-switching: is a method for generating intense short pulses (sometimes called giant pulses) of light with a laser. The basic principle is as follows: In a first phase,the gain medium is pumped, while the extraction of energy as laser light is prevented by keeping the resonator losses high (that is,the Q factor is kept low).This can be done with active or passive. The resonator losses are then suddenly reduced. As the gain is then substantially higher than the resonator losses,the intra-cavity power rises exponentially (normally starting from weak fluorescence light of the gain medium),until the gain is saturated and the power decays again.

The generated light pulse can extract a large percentage of the energy that was originally stored in the gain medium. For a high pulse energy, the gain medium must have a high energy storage capability, that is, a long upper-state lifetime, a high density of laser-active ions or atoms, and a not-too-high gain efficiency. (The latter is important because amplified spontaneous emission could otherwise limit the stored energy, and the initial loss required for preventing premature lasing would be very high.)

The most-used laser gain media for Q-switched lasers are rare-earth-doped crystals and glasses. Bulk lasers are most common, although fiber lasers can also be Q switched and can in combination with fiber amplifiers provide very high average powers.

5.3.1 Active Q Switching

Active Q switching is based on active loss modulation with a so-called Q switch. Typically, an acousto-optic active Q switching modulator is incorporated into the laser resonator. While the RF power is applied to the modulator, this introduces large losses by diffraction into the first-order beam, which leaves the resonator.The pulse is triggered by suddenly switching off the RF power.

For high pulse repetition rates, the crystal is continuously pumped, and the Q switch is triggered repetitively. For the highest pulse energies, pulsed pumping (for example, with a flashlamp) and low pulse repetition rates are used.

5.3.2 Passive Q Switching

Passive Q switching is an alternative technique, where the active modulator is replaced with a saturable absorber (a passive Q switch). In a Nd:YAG laser, for example, this could be a Cr_4^+:YAG crystal.

There are other saturable absorber crystals for other wavelengths and semiconductor saturable absorber mirrors (SESAM) for various operation wavelengths. The saturable absorber initially introduces a high optical loss. Once the gain reaches this loss level and the pulse begins to build up, the absorber is saturated, that is, its loss is reduced, which further accelerates the pulse buildup. This method is simple and cost effective (eliminating the modulator and its electronics) and is suitable for very high pulse repetition rates, but it typically leads to lower pulse energies and does not allow external triggering of the pulses.

In any case, the laser dynamics and the energy balance impose certain restrictions on the pulse parameters. For example, a higher pulse repetition rate will normally reduce the pulse energy and increase the pulse duration.

5.4 Mode locking method

A mode locked laser emits extremely short pulses on the order of tens of picoseconds down to less than 10 femto seconds. These pulses are typically separated by the time that a pulse takes to complete one round trip in the resonator cavity. Due 60 to the Fourier limit (also known as energy-time uncertainty),a pulse of such short temporal length has a spectrum which contains a wide range of wavelengths. Because of this, the laser medium must have a broad enough gain profile to amplify them all.An example of a suitable material is titanium-doped, artificially grown sapphire (Ti:sapphire).

The technique of mode locking allows the generation of laser pulses of ultra short duration from a few ten of femtoseconds to a few tens of picoseconds.Laser in which the phases of the longitudinal modes forced to maintain a fixed phase relationship to each other is called mode locked. lasers operate as a result of the resonant modes of the optical cavity which can affect the characteristics of the output beam.

When the phases of different frequency modes are synchronized, i.e., "locked together," the different modes will interfere with one another to generate a beat effect. The result is a laser output which is observed as regularly spaced pulsations.Lasers operating in this mode-locked fashion, usually produce a train of regularly spaced pulses, each having a duration of 10^{-15} (femtosecond) to 10^{12} (picosecond).A mode-locked laser can deliver extremely high peak powers than the same laser operating in the Q-switched mode. These pulses will have enormous peak powers often in the range from 10^{12} Watts peak. In lasers with only a few oscillating modes acting independently, interference between the modes can cause beating effects in the laser output, leading to random fluctuations in intensity.

In lasers with many thousands of modes, these interference effects tend to average to a near-constant output intensity, and the laser operation is known as continuous wave. If each mode operates with a fixed phase between it and the other modes, the modes of the laser will periodically all constructively interfere with one another, producing an intense burst or pulse of light.

5.4.1 Active Mode Locking

A technique of mode locking, based on active modulation of the intra-cavity losses or the round-trip phase change is called active mode locking.Active mode locking involves the periodic modulation of the resonator losses or of the round-trip phase change.

This can be achieved e.g. with an acousto optic or electro-optic modulator,a MachZehnder integrated-optic modulator,or a semiconductor electro-absorption modulator. If the modulation is synchronized with the resonator round trips, this leads to the generation of ultrashort pulses.

5.4.2 Passive Mode Locking

A technique of mode locking, based on a saturable absorber inside the laser resonator is passive mode locking. Passive mode locking method consists of placing a saturable absorber inside the cavity. Saturable absorbers are molecules having a nonlinear decrease in absorption coefficients with the increase in the irradiance of light. The saturable absorber is placed between active laser medium and mirror. If an intense pulse of light passes through the saturable absorber placed inside the laser cavity, the low-power tails (weaker modes) of the pulse are absorbed because of the absorption of dye molecules. The high-power peak of the pulse is, however, transmitted because the dye is bleached. Owing to this nonlinear absorption, the shortest and most intense fluctuation grows, while the weaker dies out.

Chapter 6

Conclusion

Light amplification by stimulated emission of radiations is a highly coherent, monochromatic, intense, highly energetic source of light. It is produced by stimulated emission of radiations. It can be of any color based on the type of lasing material used. It has several applications in medicines and other scientific fields especially due to its intense nature. Necessary precautions should be taken during its utilization.

We conclude this section by emphasizing that the concepts of spatial and temporal coherence provide only a first-order description of the laser's coherence. Higher order coherence properties will in fact discussed in Such a discussion is essential for a full appreciation of the difference between an ordinary light source and a laser. It will be shown in fact that, by virtue of the differences between the corresponding higher-order coherence properties, a laser beam is fundamentally different from an ordinary light source.

The most notable solid-state, dye and semiconductor lasers have been considered. These lasers use high-density active media and thus share a few common features. A first feature is that they generally show wide and strong absorption bands which indicates that they are generally suitable for optical pumping, this type of pumping being in fact always used for solid-state and dye lasers and sometimes also used for semiconductor.

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DECLARATION

I here by declare that this Project is my original work and has not been presented for a degree in any other universities, and that all sources of material used for the Project have been duly acknowledged.

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