LASERS AND OPTOELECTRONICS

Fundamentals, Devices and Applications

ANIL K. MAINI

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Affectionately dedicated to:
The loving memory of my parents
Shri Sukhdev Raj Maini
and
Smt Vimla Maini

Contents

Preface

Laser, an acronym for light amplification by stimulated emission of radiation (as coined by Gould in his notebooks) is a household name today. In their early stages of development and evolution, lasers were originally confined to the premises of prominent research centres such as the Bell laboratories and Hughes research laboratories and to major academic institutes such as Columbia University. More than five decades after Theodore Maiman demonstrated the first laser in May 1960 at Hughes, this is no longer the case. Lasers are undoubtedly one of the greatest inventions of the 20th century along with satellites, computers and integrated circuits. Their use in commercial, industrial, bio-medical, scientific and military applications continues to expand today.

Lasers and Optoelectronics: Fundamentals, Devices and Applications is a comprehensive treatise on the physical and engineering principles of laser operation, laser system design, optoelectronics and laser applications. It provides a first complete account of the technological and application-related aspects of the subject of lasers and optoelectronics. The book is divided into four parts: laser fundamentals; types of lasers; laser electronics and optoelectronics; and laser applications.

The first chapter of Part I (Laser Fundamentals) aims to introduce the readers to the operational fundamentals of lasers with the necessary dose of quantum mechanics. The topics discussed in Chapter 1 include the principles of laser operation; concepts of population inversion, absorption, spontaneous emission and stimulated emission; three-level and four-level lasers; basic laser resonator; longitudinal and transverse modes of operation; and pumping mechanisms. Chapter 2 discusses the special characteristics that distinguish laser radiation from ordinary light. This is followed by a discussion of the various laser parameters that interest the designers and users of laser devices and systems.

Chapters 3–5 (Part II) describe the three main types of lasers. Based on the nature of the lasing medium, lasers are classified as either solid-state lasers (Chapter 3), gas lasers (Chapter 4) and semiconductor lasers (Chapter 5). Chapter 3 is focused on the operational fundamentals of solid-state lasers, their salient features and typical applications. Gas lasers covered in Chapter 4 include helium-neon lasers, carbon dioxide lasers, metal vapour lasers, rare gas ion lasers, excimer lasers, chemical lasers and gas dynamic carbon dioxide lasers. Again, the emphasis is on operational fundamentals, salient features and typical applications of these lasers. (Dye lasers, free electron lasers and x-ray lasers are also covered in Chapter 4, although these do not belong to any of the three main categories.) Chapter 5 discusses semiconductor diode lasers, which typically emit in the visible to near-infrared bands of the electromagnetic spectrum. Optically pumped semiconductor lasers, quantum cascade lasers, lead salt lasers and antimonide lasers are also covered briefly. Topics covered in this chapter include operational fundamentals, semiconductor materials used in the fabrication of semiconductor lasers, different types of semiconductor diode lasers, characteristic parameters, handling precautions and application areas.

Part III (Chapters 7–10) provides information on the electronics that accompany most laser systems. Chapter 6 describes the basic building blocks of electronics generally used in the design of electronics packages of prominent laser sources and systems configured around them. The intention is to familiarize the readers with the operational basics of these building blocks, allowing an understanding of the specific laser electronics packages discussed in the following chapters. This chapter will particularly benefit laser and optoelectronics students and professionals who do not have a comprehensive knowledge of electronics.

Chapters 7–9 describe the electronics that feature in the three major categories of lasers. Chapter 7 deals with the design and the operational aspects of different types of power supplies, pulse repetition rate and high-voltage trigger generation circuits used in pulsed and continuous wave solid-state lasers. Chapter 8 describes the fundamentals of gas laser power supplies in terms of requirement specifications, circuit configurations and design guidelines, with particular reference to the two most commonly used gas lasers (helium-neon and carbon dioxide lasers). Power supply configurations for metal vapour lasers and excimer lasers (and to a large extent noble gas ion lasers) are similar to those used for helium-neon and carbon dioxide lasers except for minor deviations, which are discussed during the course of the text. Frequency stabilization techniques used in the case of helium-neon and carbon dioxide lasers are also discussed. Chapter 9 discusses the different topics related to semiconductor diode laser electronics. The chapter describes the common mechanisms of laser damage and the precautions which must be observed to protect them. The different topologies commonly used in the design of laser diode drive circuits and temperature controllers to meet the requirements of different applications are also described. Chapter 10 provides detailed information on the fundamentals and application circuits of different types of optoelectronic devices.

Part IV (Chapters 11–15) comprehensively covers applications of lasers and optoelectronic devices. Chapters 11, 12 and 13 cover industrial, medical and scientific applications respectively, and Chapters 14 and 15 cover military applications. The major industrial applications of lasers discussed in Chapter 11 includes cutting, welding, drilling, marking, rapid prototyping, photolithography and laser printing. The use of lasers in medical disciplines such as angioplasty, cancer diagnosis and treatment, dermatology, ophthalmology, cosmetic applications such as hair and tattoo removal and dentistry are discussed in Chapter 12. Chapter 13 describes some of the important applications of lasers in the pursuit of science and technology. Topics discussed include the use of lasers for optical metrology, laser velocimetry, laser vibrometry, electron speckle pattern interferometry, Earth and environmental studies, astronomy and holography. The use of lasers and optoelectronic devices in defence are exhaustively covered in Chapters 14 and 15.

The book is concluded with an appendix including a brief discussion on laser safety, which is of paramount importance to a wide cross-section of designers and users of laser systems.

The book covers each of the topics in its entirety from basic fundamentals to advanced concepts, thereby leading the reader logically from the basics of laser action to advanced topics in laser system design. Simple explanations of the concepts, a number of solved examples and unsolved problems and references for further reading are significant features of each chapter.

The motivation to write this book was provided by the absence of any one volume combining the technology and application-related aspects of laser and optoelectronics. The book is aimed at a wide range of readers, including: undergraduate students of physics and electronics, graduate students specializing in lasers and optoelectronics, scientists and engineers engaged in research and development of lasers and optoelectronics; and practising professionals engaged in the operation and maintenance of lasers and optoelectronics systems.

Part I

Laser Fundamentals

1

Laser Basics

1.1 Introduction

Although lasers were confined to the premises of prominent research centres such as the Bell laboratories, Hughes research laboratories and major academic institutes such as Columbia University in their early stages of development and evolution, this is no longer the case. Theodore Maiman demonstrated the first laser five decades ago in May 1960 at Hughes research laboratories. The acronym ‘laser’, Light Amplification by Stimulated Emission of Radiation, first used by Gould in his notebooks is a household name today. It was undoubtedly one of the greatest inventions of the second half of the 20th century along with satellites, computers and integrated circuits; its unlimited application potential ensures that it continues to be so even today. Although lasers and laser technology are generally applied in commercial, industrial, bio-medical, scientific and military applications, the areas of its usage are multiplying as are the range of applications in each of these categories.

This chapter, the first in Laser basics, is aimed at introducing the readers to operational fundamentals of lasers with the necessary dose of quantum mechanics. The topics discussed in this chapter include: the principles of laser operation; concepts of population inversion, absorption, spontaneous emission and stimulated emission; three-level and four-level lasers; basic laser resonator; longitudinal and transverse modes of operation; and pumping mechanisms.

1.2 Laser Operation

The basic principle of operation of a laser device is evident from the definition of the acronym ‘laser’, which describes the production of light by the stimulated emission of radiation. In the case of ordinary light, such as that from the sun or an electric bulb, different photons are emitted spontaneously due to various atoms or molecules releasing their excess energy unprompted. In the case of stimulated emission, an atom or a molecule holding excess energy is stimulated by a previously emitted photon to release that energy in the form of a photon. As we shall see in the following sections, *population inversion* is an essential condition for the stimulated emission process to take place. To understand how the process of population inversion subsequently leads to stimulated emission and laser action, a brief summary of quantum mechanics and optically allowed transitions is useful as background information.

1.3 Rules of Quantum Mechanics

According to the basic rules of quantum mechanics all particles, big or small, have discrete energy levels or states. Various discrete energy levels correspond to different periodic motions of its constituent nuclei and electrons. While the lowest allowed energy level is also referred to as the *ground state*, all other relatively higher-energy levels are called *excited states*. As a simple illustration, consider a hydrogen

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atom. Its nucleus has a single proton and there is one electron orbiting the nucleus; this single electron can occupy only certain specific orbits. These orbits are assigned a quantum number N with the innermost orbit assigned the number $N = 1$ and the subsequent higher orbits assigned the numbers $N = 2$, 3, 4 . . . outwards. The energy associated with the innermost orbit is the lowest and therefore $N = 1$ also corresponds to the ground state. Figure 1.1 illustrates the case of a hydrogen atom and the corresponding possible energy levels.

The discrete energy levels that exist in any form of matter are not necessarily only those corresponding to the periodic motion of electrons. There are many types of energy levels other than the simple-to-describe electronic levels. The nuclei of different atoms constituting the matter themselves have their own energy levels. Molecules have energy levels depending upon vibrations of different atoms within the molecule, and molecules also have energy levels corresponding to the rotation of the molecules. When we study different types of lasers, we shall see that all kinds of energy levels – electronic, vibrational and rotational – are instrumental in producing laser action in some of the very common types of lasers.

Transitions between electronic energy levels of relevance to laser action correspond to the wavelength range from ultraviolet to near-infrared. Lasing action in neodymium lasers (1064 nm) and argon-ion lasers (488 nm) are some examples. Transitions between vibrational energy levels of atoms correspond to infrared wavelengths. The carbon dioxide laser (10 600 nm) and hydrogen fluoride laser (2700 nm) are some examples. Transitions between rotational energy levels correspond to a wavelength range from 100 microns (μm) to 10 mm.

In a dense medium such as a solid, liquid or high-pressure gas, atoms and molecules are constantly colliding with each other thus causing atoms and molecules to jump from one energy level to another. What is of interest to a laser scientist however is an *optically allowed transition*. An optically allowed transition between two energy levels is one that involves either absorption or emission of a photon which satisfies the resonance condition of $\Delta E = h\nu$, where ΔE is the difference in energy between the two involved energy levels, h is Planck's constant ($= 6.626\,075\,5 \times 10^{-34}$ J s or $4.135\,669\,2 \times 10^{-15}$ eV s) and ν is frequency of the photon emitted or absorbed.

1.4 Absorption, Spontaneous Emission and Stimulated Emission

Absorption and emission processes in an optically allowed transition are briefly mentioned in the previous section. An electron or an atom or a molecule makes a transition from a lower energy level to a higher energy level only if suitable conditions exist. These conditions include:

1. the particle that has to make the transition should be in the lower energy level; and
2. the incident photon should have energy ($= h\nu$) equal to the transition energy, which is the difference in energies between the two involved energy levels, that is, $\Delta E = h\nu$.

If the above conditions are satisfied, the particle may make an absorption transition from the lower level to the higher level (Figure 1.2a). The probability of occurrence of such a transition is proportional to both the population of the lower level and also the related Einstein coefficient.

There are two types of emission processes, namely: *spontaneous emission* and *stimulated emission*. The emission process, as outlined above, involves transition from a higher excited energy level to a lower energy level. Spontaneous emission is the phenomenon in which an atom or molecule undergoes a transition from an excited higher-energy level to a lower level without any outside intervention or stimulation, emitting a resonance photon in the process (Figure 1.2b). The rate of the spontaneous emission process is proportional to the related Einstein coefficient. In the case of stimulated emission (Figure 1.2c), there first exists a photon referred to as the stimulating photon which has energy equal to the resonance energy ($h\nu$). This photon perturbs another excited species (atom or molecule) and causes it to drop to the lower energy level, emitting a photon of the same frequency, phase and polarization as that of the stimulating photon in the process. The rate of the stimulated emission process is proportional to the population of the higher excited energy level and the related Einstein coefficient. Note that, in the case of spontaneous emission, the rate of the emission

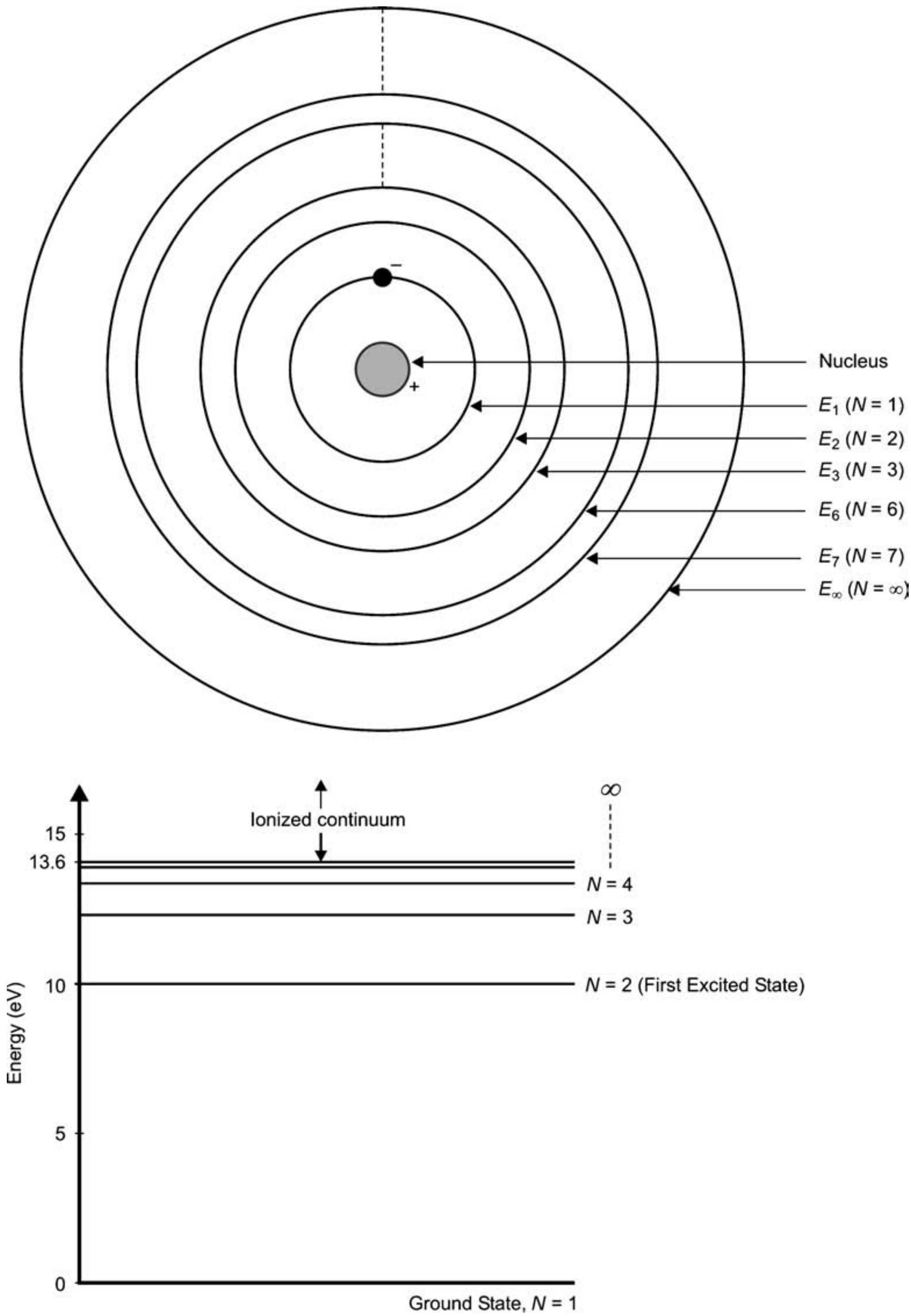

Figure 1.1 Energy levels associated with the hydrogen atom.

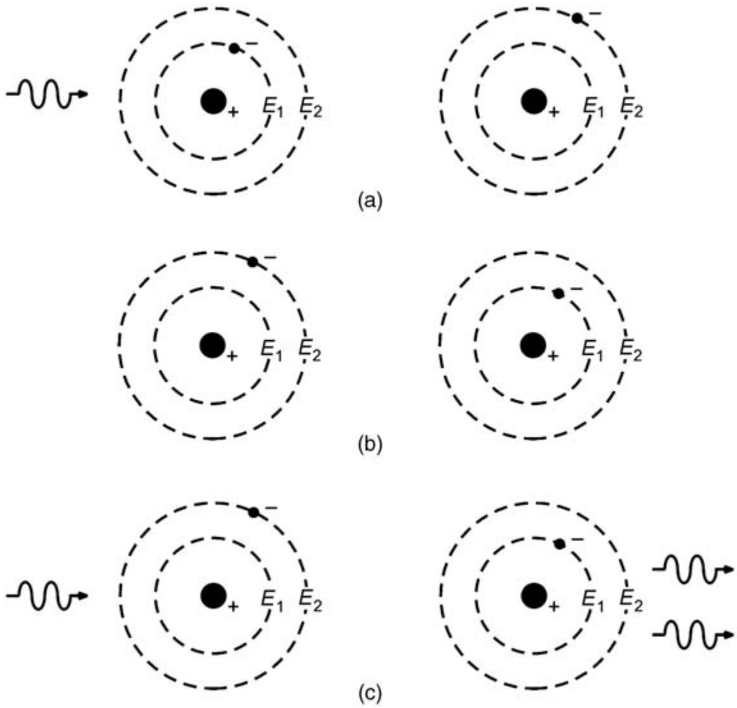

Figure 1.2 Absorption and emission processes: (a) absorption; (b) spontaneous emission; and (c) stimulated emission.

process does not depend upon the population of the energy state from where the transition has to take place, as is the case in absorption and stimulated emission processes. According to the rules of quantum mechanics, absorption and stimulated emission are analogous processes and can be treated similarly.

We have seen that absorption, spontaneous emission and stimulated emission are all optically allowed transitions. Stimulated emission is the basis for photon multiplication and the fundamental mechanism underlying all laser action. In order to arrive at the necessary and favourable conditions for stimulated emission and set the criteria for laser action, it is therefore important to analyze the rates at which these processes are likely to occur. The credit for defining the relative rates of these processes goes to Einstein, who determined the well-known '*A*' and '*B*' constants known as Einstein's coefficients. The '*A*' coefficient relates to the spontaneous emission probability and the '*B*' coefficient relates to the probability of stimulated emission and absorption. Remember that absorption and stimulated emission processes are analogous phenomenon. The rates of absorption and stimulated emission processes also depend upon the populations of the lower and upper energy levels, respectively.

For the purposes of illustration, consider a two-level system with a lower energy level 1 and an upper excited energy level 2 having populations of N_1 and N_2, respectively, as shown in Figure 1.3a. Einstein's coefficients for the three processes are B_{12} (absorption), A_{21} (spontaneous emission) and B_{21} (stimulated emission). The subscripts of the Einstein coefficients here represent the direction of transition. For instance, B_{12} is the Einstein coefficient for transition from level 1 to level 2. Also, since absorption and stimulated emission processes are analogous according to laws of quantum mechanics, $B_{12} = B_{21}$. According to Boltzmann statistical thermodynamics, under normal conditions of thermal equilibrium atoms and molecules tend to be at their lowest possible energy level, with the result that population decreases as the energy level increases. If E_1 and E_2 are the energy levels

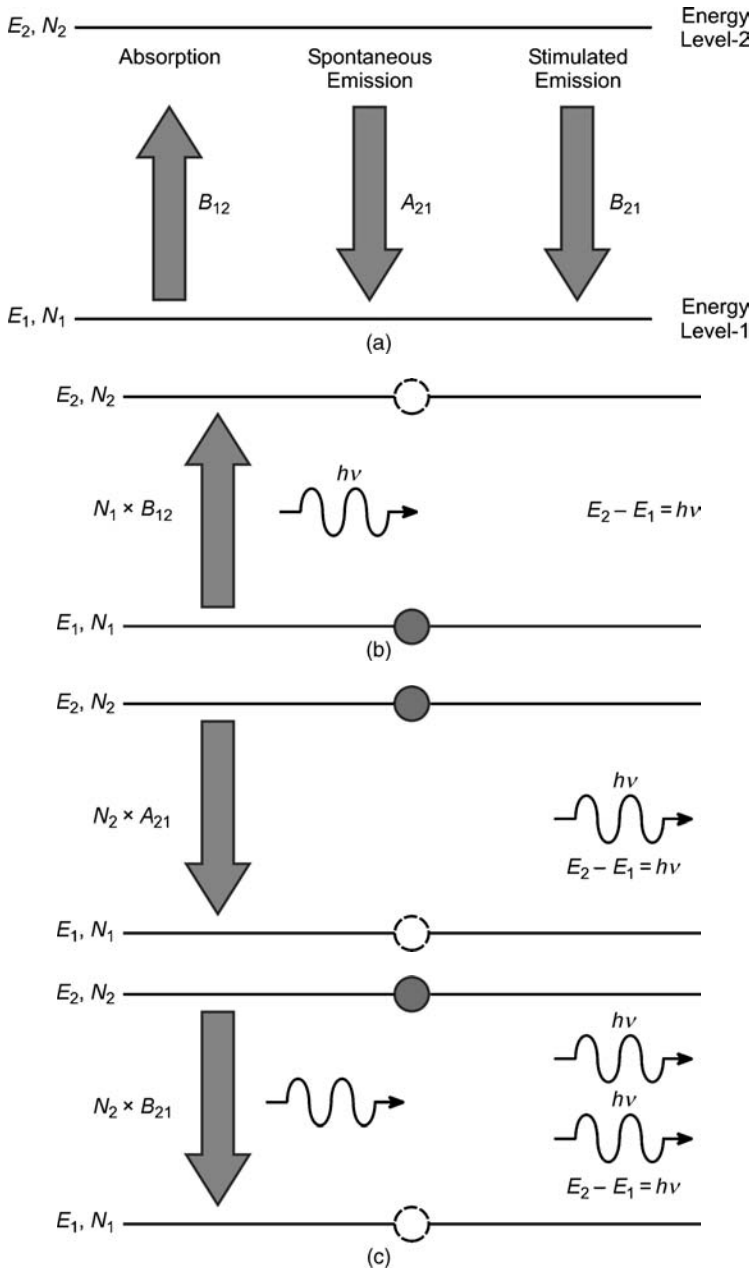

Figure 1.3 Absorption, spontaneous emission and stimulated emission.

associated with level 1 and level 2, respectively, then the populations of these two levels can be expressed by Equation 1.1:

$$\frac{N_2}{N_1} = \exp[-(E_2 - E_1)/kT] \tag{1.1}$$

where

$k =$ Boltzmann constant $= 1.38 \times 10^{-23}\,\text{J K}^{-1}$ or $8.6 \times 10^{-23}\,\text{eV K}^{-1}$
$T =$ absolute temperature in degrees Kelvin

Under normal conditions, N_1 is greater than N_2. When a resonance photon ($\Delta E = h\nu$) passes through the species of this two-level system, it may interact with a particle in level 1 and become absorbed, in the process raising it to level 2. The probability of occurrence of this is given by $B_{12} \times N_1$ (Figure 1.3b). Alternatively, it may interact with a particle already in level 2, leading to emission of a photon with the same frequency, phase and polarization. The probability of occurrence of this process, known as stimulated emission, is given by $B_{21} \times N_2$ (Figure 1.3d). Yet another possibility is that a particle in the excited level 2 may drop to level 1 without any outside intervention, emitting a photon in the process. The probability of this spontaneous emission is A_{21} (Figure 1.3c). The spontaneously emitted photons have the same frequency but have random phase, propagation direction and polarization.

If we analyze the competition between the three processes, it is clear that if $N_2 > N_1$ (which is not the case under the normal conditions of thermal equilibrium), there is the possibility of an overall photon amplification due to enhanced stimulated emission. This condition of $N_2 > N_1$ is known as *population inversion* since $N_1 > N_2$ under normal conditions. We shall explain in the following sections why population inversion is essential for a sustained stimulated emission and hence laser action.

Example 1.1

Refer to Figure 1.4. It shows the energy level diagram of a typical neodymium laser. If this laser is to be pumped by flash lamp with emission spectral bands of 475–525 nm, 575–625 nm, 750–800 nm and 820–850 nm, determine the range of emission wavelengths that would be absorbed by the active medium of this laser and also the wavelength of the laser emission.

Solution

1. Referring to the energy level diagram of Figure 1.4, two edges of the absorption band correspond to energy levels of 12 500 cm^{-1} and 13 330 cm^{-1}. Corresponding wavelengths (of photons) that would have these energy levels are computed as:

   Wavelength corresponding to 12 500 cm^{-1} = (1/12 500) cm = (10^7/12 500) nm = 800 nm
   Wavelength corresponding to 13 330 cm^{-1} = (1/13 330) cm = (10^7/13 330) nm = 750.19 nm ≅ 750 nm

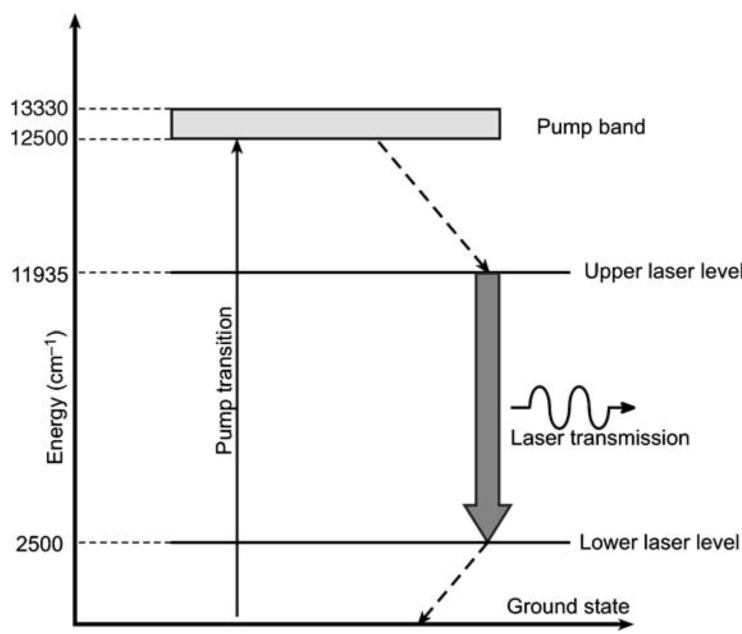

Figure 1.4 Example 1.1: Energy level diagram.