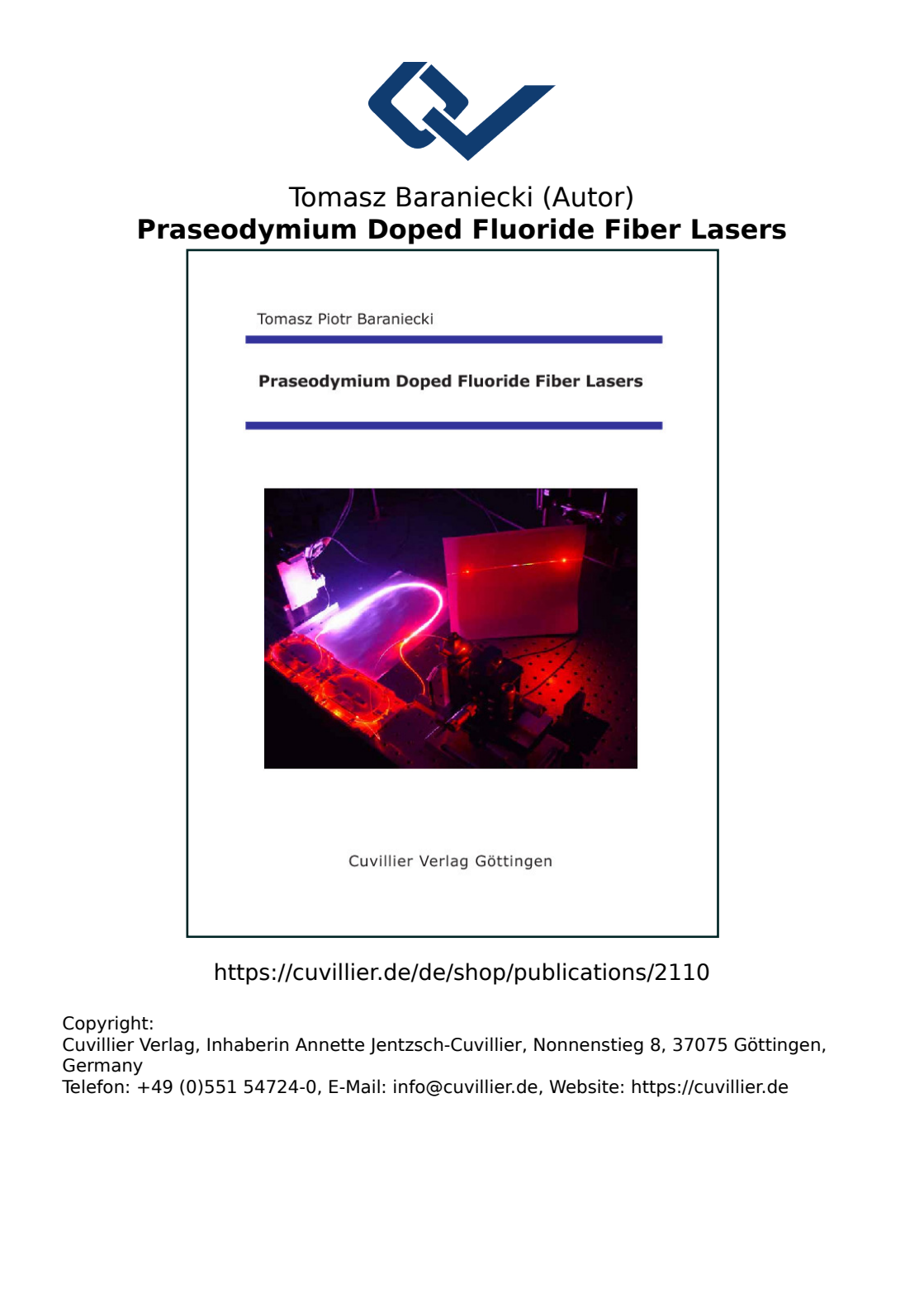

Tomasz Baraniecki (Autor)

Praseodymium Doped Fluoride Fiber Lasers

https://cuvillier.de/de/shop/publications/2110

Introduction

The subject of rare earth doped fiber lasers and amplifiers is an interesting and promising research field because it provides low-cost laser sources and amplifiers at wavelengths that are important for telecommunication, medicine, sensors, metrology and spectroscopy.

Laser action is produced by introduction of suitable rare earth ions into the core of a single mode fiber. The considerable advantages of the fiber configuration arise from the fact that the pump radiation travels along the axis of the fiber and is guided by the core, as is the lasing radiation. Therefore, the coupling between the pump radiation and the ions is very effective, while the pump intensity is very high because of the small core diameter. These factors enable successful lasing of transitions that have no conventional solid-state analogue, via pumping of very weak absorptions using long lengths of fiber. In conventional crystal lasers, on the other hand, high power density is achieved by tight focusing which then limits the effective pumping length through divergence. Fiber lasers are small, robust, flexible, and give easy access to the laser cavity, thus enabling the operations of Q-switching, mode-locking and line-narrowing to be carried out. The inherent high beam quality of single mode fiber lasers is more or less independent of the output power in contrast to laser diodes. Because of the large fluorescence linewidth, large tuning ranges can also be obtained. Fiber lasers are also no longer restricted to low power operation. Cladding pumping enables light from high power pump sources to be used efficiently and converted to multiwatt output powers with a brightness enhanced by more than two orders of magnitude.

Rare earth doped fluoride glass fibers have been shown to be excellent laser materials. Besides their unique properties for fiber lasers, they offer more metastable levels than silica fibers, thus improving performance, adding new wavelengths and allowing easier upconversion lasing. Typical upconversion fiber lasers are pumped in the near infrared but emit laser radiation in the visible range by subsequent absorption of two or more pump photons. For this multi-stage process to be efficient, besides the large interaction length inherent to fiber lasers, long lifetimes of the respective energy levels are necessary, and therefore low phonon energy glasses are needed. In silica, the higher energy levels of dopant ions relax very fast by excitation of vibrations of the glass matrix since it has high phonon energies. In practice, the most important low phonon energy glasses are heavy metal fluoride glasses of which the ZBLAN glass is the most famous type. Rare earth ions are particularly appropriate for upconversion lasers because they have numerous long-living metastable levels which store population during the upconversion process. Upconversion lasers may provide a useful route to the development of visible lasers pumped by cheap semiconductor lasers operating in the near infrared region of the spectrum.

Upconversion fiber lasers operating in the red, green, and blue spectral range offer a good alternative to air-cooled ion lasers and frequency-doubled solid-state lasers. The laser transitions of the Pr^{3+} ion are attractive, because laser operation at blue, green, orange and red wavelengths can all be obtained. Additional doping with Yb^{3+} ions enables to obtaining these laser transitions using only one pump wavelength.

In this work, we will describe different aspects of laser operation. Special attention is paid to the Pr^{3+}/Yb^{3+} doped fiber lasers emitting in the visible spectral range. The study presented in this work consists of seven chapters, and a short description of their contents will be given below.

Chapter 1. This chapter provides fundamental information about lasers and basic principles of laser operation. Absorption, spontaneous and stimulated emission are described as well as the creation of the population inversion.

Chapter 2. In this chapter, properties of laser materials are discussed with special attention to rare earth ions in a glass host. The next object of discussion is interactions between the ions. The upconversion pumping process in praseodymium ions is described in detail. Nonradiative relaxation plays an important role in the upconversion process, and therefore, it is also reviewed.

Chapter 3. The spectroscopic investigations of praseodymium in the glass matrix and their analysis are explained in this chapter. A number of absorption as well as emission lines are investigated in ZBLAN and IBZP glass systems. The fluorescence lifetime of the upper laser level is a very important parameter; therefore, lifetime measurements are performed for both glass types.

Chapter 4. After an introduction of the structure of an optical fiber in general and loss mechanisms, fiber lasers emitting in the visible spectral range are described with a focus on fiber lasers doped with Pr^{3+}. This chapter also contains a comparison of bulk and fiber lasers as well as fiber laser applications. Semiconductor diode lasers and second harmonic generation are presented as another method to generate light in the visible spectrum range.

Chapter 5. Results of measurements on visible fiber lasers in Fabry-Perot configuration are reported in this chapter. We begin with a description of the setup, and then performances of fiber lasers emitting at red, green and blue wavelengths are presented. In addition, investigations of the optimal pump wavelength, mirror reflectivity and fiber length are shown. We also concentrate on short- and long-term stability of fiber lasers. Finally, relaxation oscillations and noise suppression are discussed.

Chapter 6. Here the results of red, all-fiber fiber laser measurements are presented with a focus on the ring laser. This laser makes use of directional couplers; therefore, this chapter begins with a describtion of the fabrication of these components. Next, the glue-splice technique is presented as a solution to the connection problems between fluoride and silica fibers. Fiber Bragg gratings and loop mirrors are presented as other ways to construct an all-fiber laser setup.

Chapter 7. In the last chapter, we the concentrate on tunability of the praseodymium doped fiber lasers. After presentating the configuration used to construction tunable lasers, the orange-red tunable fiber laser is described. Furthermore, a superfluorescence source based on a similar setup is presented.

1 Laser theory

This chapter will provide fundamental information about lasers. It describes the basic principles of laser operation. In 1917, Albert Einstein showed that the process of stimulated emission must exist, but it was not before 1960 that T. H. Maiman was able to demonstrate laser action for the first time [1]. Basic principles and the construction of lasers are relatively simple but on the other hand, a rigorous analysis of the physics of lasers is quite difficult. Therefore, the following approach is very much simplified.

1.1 Interaction of radiation with matter

In order to understand the operation of a laser we have to know some of the principles which govern the interaction of radiation and matter. Atomic systems such as atoms, ions, and molecules can exist only in discrete energy states. A change from one energy state to another is called a transition. To simplify the discussion, let us consider an idealized material with just two energy levels, 1 and 2, having populations of N_1 and N_2, respectively (Figure 1.1). The total number of atoms in these two levels N_0 is assumed to be constant [2]:

$$N_1 + N_2 = N_0 . \tag{1.1}$$

If the system is in the lower level E_1 then, in the presence of photons, it may be excited to the upper level E_2 by absorbing a photon. Alternatively, if the system is in the level E_2 it may return to the ground state with the emission of a photon. The energy difference between the levels must be compensated by the emission or absorption of radiant energy. It is given by the relation [3]:

$$\mathrm{h}\nu_{21} = \frac{hc}{\lambda} = E_2 - E_1 , \tag{1.2}$$

where h is Planck's constant, c the velocity of light in a vacuum, ν_{21} the frequency, and λ the wavelength of the photon. E_2 and E_1 are two discrete energy levels. The emission process may occur in two ways. The first is the *spontaneous emission* process in which the system drops to the lower level in a completely random way. The second is the *stimulated emission* process in which the system is 'triggered' by the presence of another photon to make the transition. The photon must have the proper energy corresponding to the energy difference between the original state and a lower energy level. The stimulated photon has the same frequency, same state of polarization, same phase, and it propagates in the same direction as the stimulating photon. The original radiation is still present, and so the radiation intensity has been amplified. This is the origin of the acronym LASER: '**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation'. The three processes are shown in Figure 1.1. The horizontal straight lines represent the level; the wavy arrows represent photons; and the vertical arrows represent the transitions of electrons from one level to another. The black dot indicates the state of the atom before and after the transition.

1.1.1 Absorption

If a quasi monochromatic electromagnetic wave of frequency v_{21} passes through an atomic system with energy gap hv_{21}, then the population of the lower level will be depleted at a rate proportional both to the radiation density $\rho(v)$ and to the population N_1 of that level [2]:

$$\frac{\partial N_1}{\partial t} = -B_{12}\rho(v)N_1, \tag{1.3}$$

where B_{12} is the coupling constant of radiation and matter for the absorption process (Einstein coefficient). The product $B_{12}\rho(v)$ can be interpreted as the probability per unit frequency that transitions are induced by the electromagnetic field.

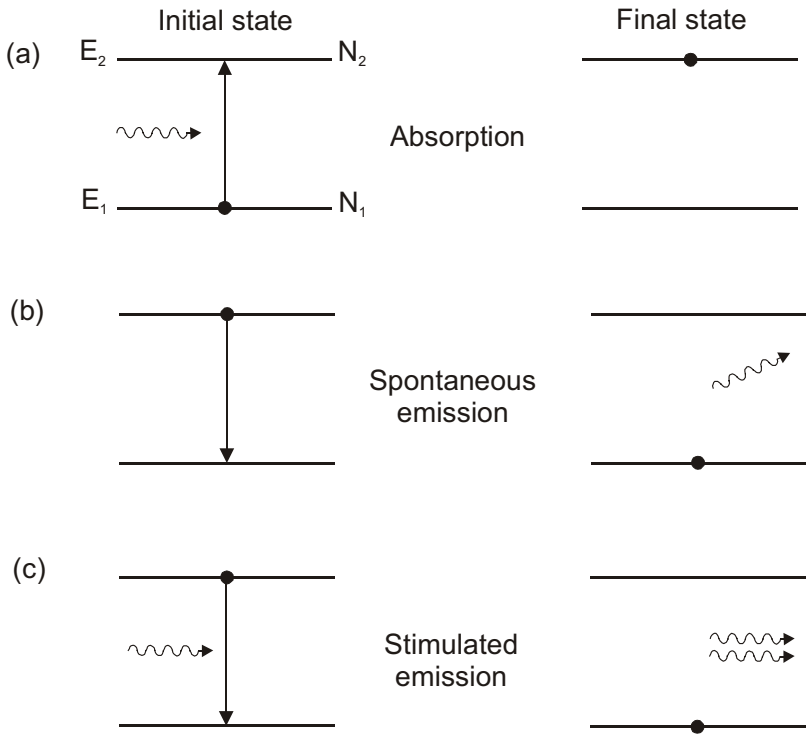

Figure 1.1: Schematic diagram illustrating (a) absorption, (b) spontaneous emission and (c) stimulated emission [1]

1.1.2 Spontaneous emission

After a couple of atoms have been excited to the upper level, the population of the upper level decays spontaneously to the lower level at a rate proportional to the upper level population [2]:

$$\frac{\partial N_2}{\partial t} = -A_{21}N_2, \tag{1.4}$$

where A_{21} is the coupling constant for the spontaneous emission process. This coefficient gives the probability for an atom in level 2 to decay spontaneously to the lower level 1 within

a unit of time. Spontaneous emission is characterized by the lifetime of the electron in the excited state in which it will spontaneously return to the lower state and radiate away the energy difference. This radiation lifetime is connected with A_{21} by the relation:

$$\tau_{21} = A_{21}^{-1}. \tag{1.5}$$

In general, the reciprocal transition probability of a process is called its lifetime.

1.1.3 Stimulated emission

As already mentioned, emission takes places not only spontaneously but also under stimulation. The atom gives a quantum to the radiation field by induced emission [2]:

$$\frac{\partial N_2}{\partial t} = -B_{21}\rho(v)N_2, \tag{1.6}$$

where B_{21} is the coupling constant for the stimulated emission process.

If we combine absorption, spontaneous and stimulated emission, as presented in (1.3), (1.4) and (1.6) we can write for the change of the upper and lower level populations in our two-level model:

$$\frac{\partial N_1}{\partial t} = -\frac{\partial N_2}{\partial t} = B_{21}\rho(v)N_2 - B_{12}\rho(v)N_1 + A_{21}N_2. \tag{1.7}$$

For a system in thermal equilibrium, the number of transitions per unit time from E_1 to E_2 must be equal to the number of transitions from E_2 to E_1. Hence we have

$$\underset{\text{Spontaneous emission}}{N_2 A_{21}} + \underset{\text{Stimulated emission}}{N_2\rho(v)B_{21}} = \underset{\text{Absorption}}{N_1\rho(v)B_{12}}. \tag{1.8}$$

Thus,

$$\rho(v) = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1}. \tag{1.9}$$

The populations of the energy levels 1 and 2 in thermal equilibrium are given by Boltzmann statistics to [1]:

$$\frac{N_1}{N_2} = \frac{g_1}{g_2}\exp\left(\frac{E_2 - E_1}{kT}\right) = \frac{g_1}{g_2}\exp\left(\frac{hv_{21}}{kT}\right), \tag{1.10}$$

where k is Boltzmann's constant and T is the absolute temperature of the material. In general, the probability for occupation of all energy levels is not the same, and g_j is the degeneracy of the jth level. Hence, substituting eq. (1.10) into eq. (1.9) yields:

$$\rho(v) = \frac{A_{21}/B_{21}}{\left[\frac{g_1}{g_1}\frac{B_{12}}{B_{21}}\exp\left(\frac{hv_{21}}{kT}\right)\right]-1}. \tag{1.11}$$

As we consider the atom system to be in thermal equilibrium, it must give rise to radiation which is identical with blackbody radiation, the density of which can be described by [1]:

$$\rho(v) = \frac{8\pi hv^3}{c^3}\left(\frac{1}{\exp(hv/kT)-1)}\right). \tag{1.12}$$

Comparing eqs. (1.11) and (1.12) , we can write [2]:

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hv}{c^3} \qquad \text{and} \qquad B_{21} = \frac{g_1 B_{12}}{g_2}. \tag{1.13}$$

The relation between the A's and B's are known as Einstein's relations, and A_{21}, B_{12} and B_{21} are Einstein's constants. Equations (1.13) are very important because they show a connection among three different radiation processes: spontaneous emission, absorption, and stimulated emission. A particular experiment may emphasize one or another coefficient, the results may be applied to a completely different one, e.g. an absorption experiment yields information on the stimulated emission coefficient.

1.2 Creation of population inversion

At absolute zero temperature, Boltzmann's statistic in equation (1.10) predicts that all atoms will be in the ground state. Thermal equilibrium at any temperature requires that a state with a lower energy is more densely populated than a state with a higher energy. Absorption and emission probabilities are always independent of the population distribution among the levels. As long as the population of the higher energy levels is smaller than that of the lower one, the number of absorption transitions is larger than that of emission transitions; there is an overall attenuation of radiation. If the numbers of atoms in both states are equal to $g_2{:}g_1$, the number of emissions becomes equal to the number of absorptions, and the material is transparent for the incident radiation. As soon as the population of the higher level becomes larger than that of the lower level, emission processes dominate and the radiation is amplified during its passage through the material. Therefore, for achieving laser amplification, we must create the following condition:

$$N_2 g_2 > N_1 g_1 ; \tag{1.14}$$

i.e., we must create a so-called *population inversion*. Population inversion is clearly an abnormal situation, it is never observed at thermal equilibrium. In order to obtain population inversion, we must have a source of energy to populate the upper level; this process is commonly referred to as *pumping.* The point at which the population of both states is equal to $g_2{:}g_1$, is called the inversion threshold.

It is impossible to achieve a population inversion by optical pumping in an electronic system with only two energy levels. For a simple system with no degeneracy, e.g. one with $g_1 = g_2$, we see from eq. (1.13) that $B_{21} = B_{12}$. Hence, if atoms are excited into the upper level the probabilities of further absorption or stimulated emission are equal even with very intensive pumping. The best that can be achieved with a two-level system is equality of population of the two levels; the material becomes transparent. This situation is often referred to as two-level saturation.

As a consequence we must look for materials with more than two levels. Laser materials generally have a large number of energy levels, but only three or four of them will be directly involved in laser operation. The three-level system is illustrated by Figure 1.2a.

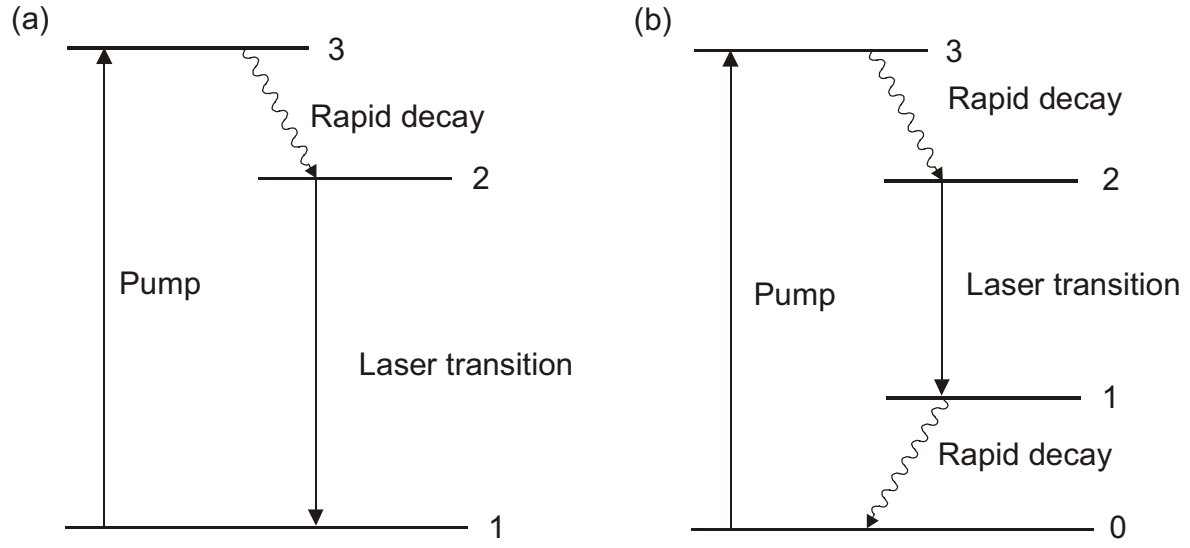

Figure 1.2: Simplified energy level diagram of (a) three-level and (b) four-level laser

Initially, all atoms of the laser material are in the lowest level 1. An auxiliary radiation pump source excites the atoms. The pump radiation raises an atom from the ground state to the pump band, level 3. Most of the excited atoms are transferred by fast radiationless transition into the intermediate level 2. In this process the energy lost by the atom is transferred to the lattice and converts to heat. With higher pump power population inversion between level 2 and 1 is achieved. Finally, the atoms return to the ground level by the emission of a photon. This transition is responsible for a laser's action [2]. It is necessary that the rate of radiationless transfers from level 3 to level 2 is fast compared to the other spontaneous transition rates. Therefore, the lifetime of level 2 should be large; it should be a metastable level. This allows for a large build-up in the number of atoms in level 2. The relatively long lifetime of the metastable level provides a mechanism by which inverted population can be achieved. The main advantage of the three-level system is that the atoms are in effect pumped directly from level 1 into the metastable level 2 with only a pause as they pass through level 3. But the three-level system has the drawback that level 1 is the ground level which normally hosts almost all the atoms. To achieve a population inversion between

levels 2 and 1 in a non-degenerated system, half of all the atoms must be moved to level 2, and so intensive pumping is needed. In a degenerated system, the population ratio $g_2:g_1$ has to be reached.

Figure 1.2b shows a four-level laser system. The pump transition raises atoms again from the ground state (now level 0) to level 3. As in the case of the three-level system, the atoms so excited will decay fast to level 2. The laser transition proceeds now to the fourth, terminal level 1, which is situated above the ground state. From here the atoms undergo a rapid nonradiative transition to the ground level [2]. In a true four-level system, the terminal laser level 1 will always be empty, hence a population inversion of the 2→1 transition can occur even with a small pump power; the high pump rate necessary in a three-level system is no longer needed. Therefore, three-level lasers have higher threshold powers than four-level laser systems, and four-level schemes are to be preferred for this reason. However, by a combination of favourable circumstances, it is possible to overcome the disadvantage of the three-level scheme.

1.3 The laser idea

The laser, despite its name, is more an analogue to an oscillator than to an amplifier. In an electronic oscillator, an amplifier tuned to a particular frequency is provided with positive feedback and, when switched on, any electrical noise signal of the appropriate frequency appearing at the input will be amplified. The input is amplified and the output is fed back to the input, where it undergoes further amplification. The process continues indefinitely until a large output is produced. The amplifier saturates at high input voltages, as it cannot produce a larger output than the supply voltage. The system reaches a steady state in which an output signal is created at the frequency of the resonant amplifier.

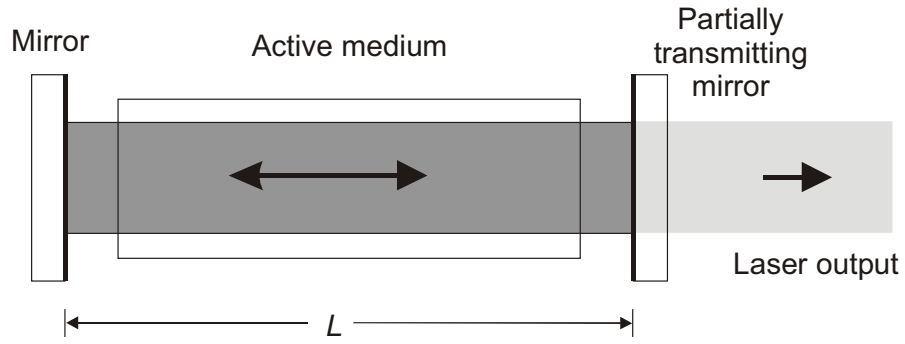

Figure 1.3: A laser consists of an active medium placed within an optical resonator.

In the laser, positive feedback may be obtained by placing the gain medium in an optical resonator, which reflects the light back and forth between its mirrors, e.g. in a Fabry-Perot resonator which is schematically shown in Figure 1.3. The initial stimulus is provided by any spontaneous transition between appropriate energy levels in which the emitted photon travels along the axis of the system. The signal is amplified as it passes through the medium and fed

back by the mirrors. As the oscillation power grows the amplifier saturates and the gain decreases below its initial value. A stable condition is reached when the reduced gain is equal to the loss. The gain then just compensates the loss so that the cycle of amplification and feedback is repeated without change, and a steady-state oscillation occurs. Output coupling is achieved by making one of the resonator mirrors partially transparent.

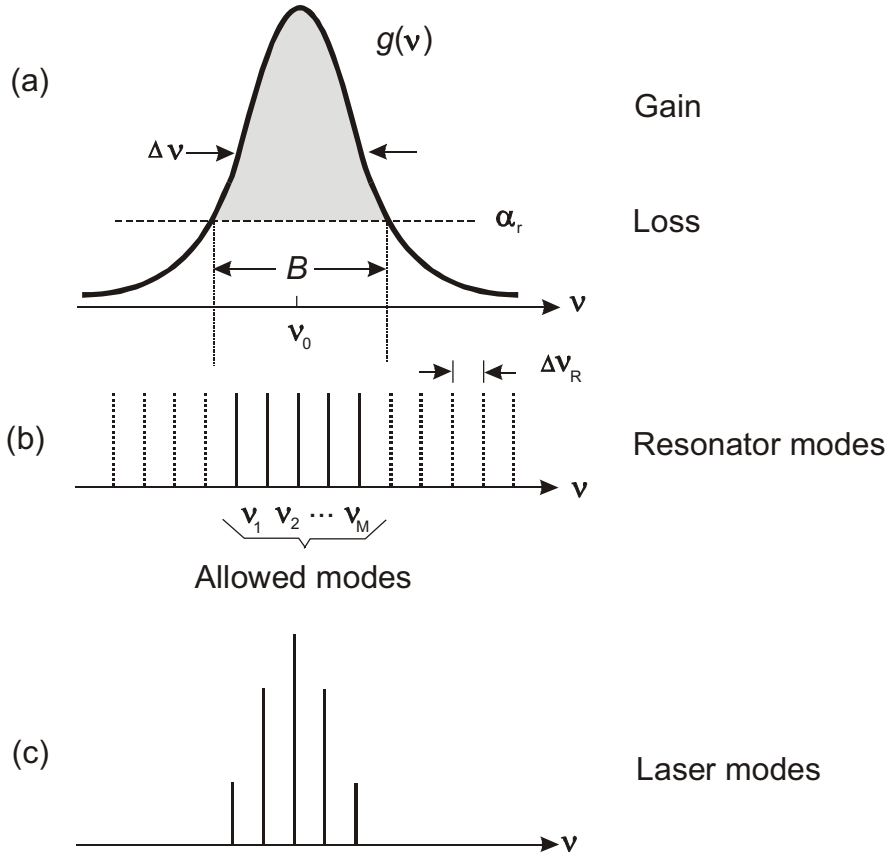

Figure 1.4: (a) Gain coefficient of a laser amplifier and the loss coefficient (dotted region), (b) resonator modes, (c) possible laser modes

As already mentioned, optical feedback is achieved by placing the active medium in an optical resonator. A Fabry-Perot resonator, comprising two mirrors separated by a distance L, contains the active medium. The resonator sustains only frequencies that correspond to a round-trip phase shift of 2π. Resonator modes are separated by the frequency:

$$\nu_R = \frac{c}{2L}. \tag{1.15}$$

The spectral distribution of the laser radiation generated is determined both by the atomic lineshape of the active medium and by the resonator modes. This is illustrated by two conditions for a laser [4]: