Chapter 7

Lasers

After having derived the quantum mechanically correct suszeptibility for an inverted atomic system that can provide gain, we can use the two-level model to study the laser and its dynamics. After discussing the laser concept briefly we will investigate various types of gain media, gas, liquid and solid-state, that can be used to construct lasers and amplifiers. Then the dynamics of lasers, threshold behavior, steady state behavior and relaxation oscillations are discussed. A short introduction in the generation of high energy and ultrashort laser pulses using Q-switching and mode locking will be given at the end.

7.1 The Laser (Oscillator) Concept

Since the invention of the vacuum amplifier tube by Robert von Lieben and Lee de Forest in 1905/06 it was known how to amplify electromagnetic waves over a broad wavelength range and how to build oscillator with which such waves could be generated. This was extended into the millimeter wave region with advances in amplifier tubes and later solid-state devices such as transistors. Until the 1950's thermal radiation sources were mostly used to generate electromagnetic waves in the optical frequency range. The generation of coherent optical waves was only made possible by the Laser. The first amplifier based on discrete energy levels (quantum amplifier) was the MASER (Microwave Amplification by Stimulated Emission of Radiation), which was invented by Gordon, Townes and Zeiger 1954. In 1958 Schawlow and Townes proposed to extend the MASER principle to the optical regime.

The amplification should arise from stimulated emission between discrete energy levels that must be inverted, as discussed in the last section. Amplifiers and oscillators based on this principle are called LASER (Light Amplification by Stimulated Emission of Radiation). Maiman was the first to demonstrate a laser based on the solid-state laser material Ruby.

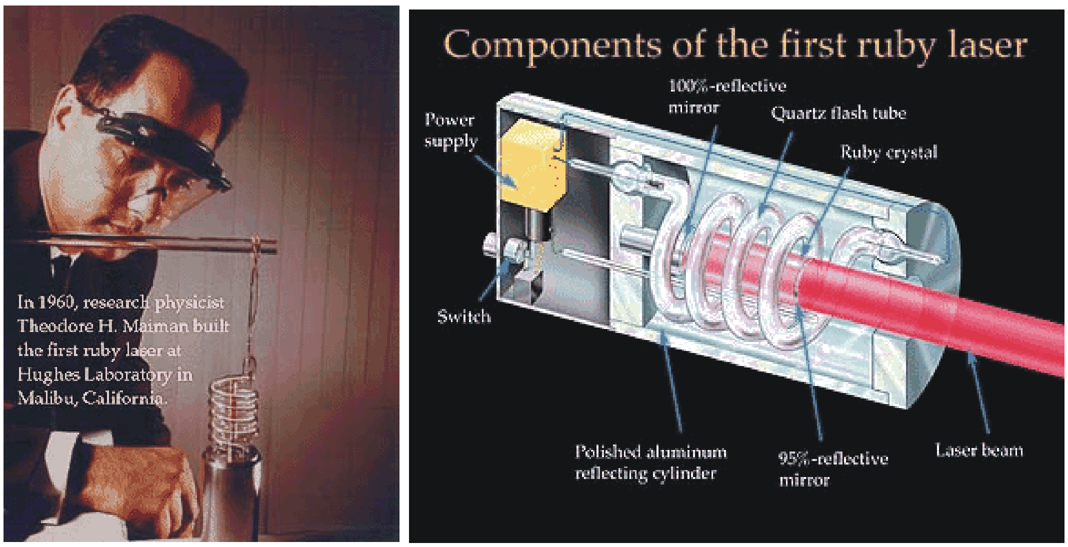

Figure 7.1: Theodore Maiman with the first Ruby Laser in 1960 and a cross sectional view of the first device [4].

The first HeNe-Laser, a gas laser followed in 1961. It is a gas laser built by Ali Javan at MIT, with a wavelength of 632.8 nm and a linewidth of only 10kHz.

The basic principle of an oscillator is a feedback circuit that is unstable, i.e. there is positive feedback at certain frequencies or certain frequency ranges, see Figure 7.2. It is the feedback circuit that determines the frequency of oscillation. Once the oscillation starts, the optical field will build up to an intensity approaching, or even surpassing, the saturation intensity of the amplifier medium by many times, until the amplifier gain is reduced to a value equal to the losses that the signal experiences after one roundtrip in the feedback loop, see Figure 7.3

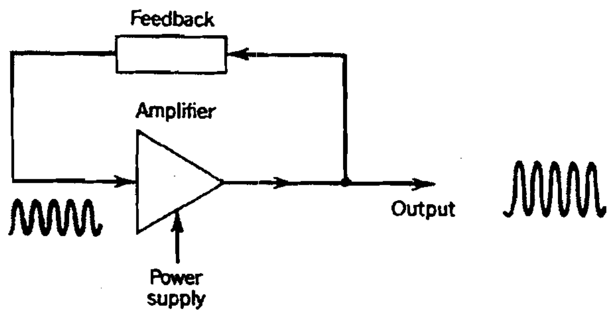

Figure 7.2: Principle of an oscillator circuit: an amplifier with positive feedback [6] p. 495.

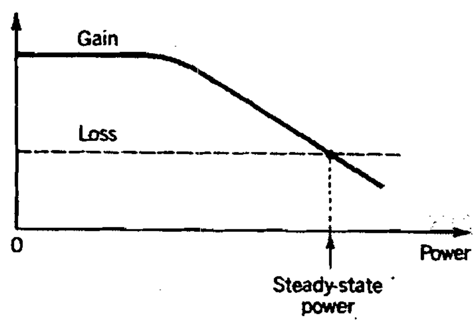

Figure 7.3: Saturation of amplification with increasing signal power leads to a stable oscillation [6], p. 496.

In the radio frequency range the feedback circuit can be an electronic feedback circuit. At optical frequencies we use an optical resonator, which is in most cases well modeled as a one-dimensional Fabry-Perot resonator, which we analysed in depth in section 7.4. We already found back then that the transfer characterisitcs of a Fabry-Perot resonator can be understood as a feedback structure. All we need to do to construct an oscillator is provide amplification in the feedback loop, i.e. to compensate in the resonator for eventual internal losses or the losses due to the output coupling via the mirrors of the Fabry-Perot, see Figure 7.4.We have already discussed in section

2.6.2 various optical resonators, which have Gaussian beams as the fundamental resonator modes. One can also use waveguides or fibers that have semitransparent mirrors at its ends or form rings as laser resonators. In the latter ones output coupling of radiation is achieved with waveguide or fiber couplers in the rings.

Today lasers generating light continuosly or in the form of long, nanosecond, or very short, femtosecond pulses can be built. Typically these lasers are Q-switched or mode-locked, respectively. The average power level can vary from microwatt to kilowatts.

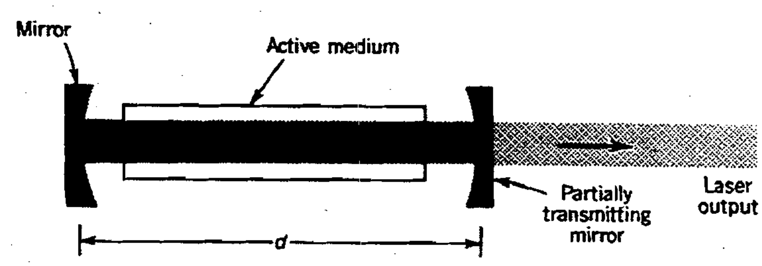

Figure 7.4: A laser consists of an optical resonator where the internal losses and/or the losses due to partially reflecting mirrors are compensated by a gain medium inside the resonator [6], p. 496.

7.2 Laser Gain Media

Important characteristics of laser gain media are whether it is a solid, a gase or liquid, how inversion can be achieved and what the spectroscopic paratmeters are, i.e. upperstate lifetime, $\tau_L = T_1$, linewdith $\Delta f_{FWHM} = \frac{2}{T_2}$ and the crosssection for stimulated emission.

7.2.1 Three and Four Level Laser Media

As we discussed before inversion can not be achieved in a two level system by optical pumping. The coherent regime is typically inaccesible by typcial optical pump sources. Inversion by optical pumping can only be achieved when using a three or four-level system, see Figures 7.5 and 7.6

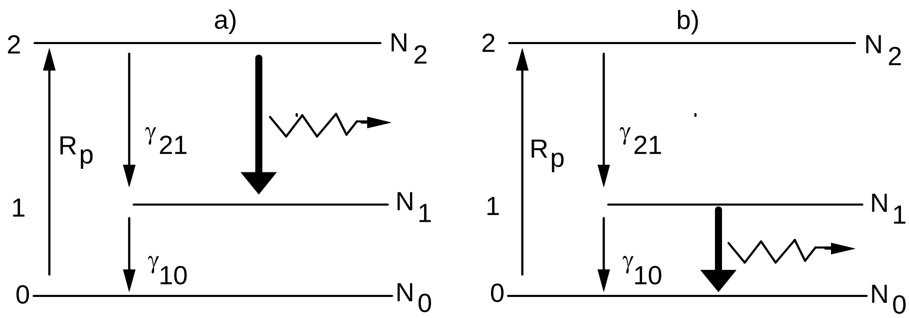

Figure 7.5: Three-level laser medium.

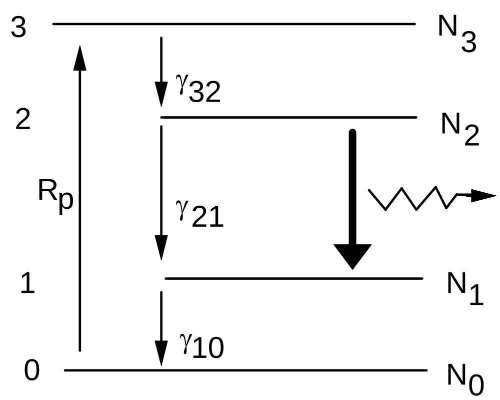

Figure 7.6: Four-level laser medium.

If the medium is in thermal equilibrium, typically only the ground state is occupied. By optical pumping with an intense lamp (flash lamp) or another laser one can pump a significant fraction of the atoms from the ground state with population N_0 into the excited state N_3 both for the three level laser operating according to scheme shown in figure 297 (a) or N_4 in the case of the four level laser, see Figure 7.6. If the relaxation rate γ_{10} is very fast compared to γ_{21}, where the laser action should occur inversion can be achieved, i.e. $N_2 > N_1$. For the four level laser the relaxation rate γ_{32} should also be fast in comparison to γ_{21}. These systems are easy to analyze in the rate equation approximation, where the dipole moments are already adiabatically eliminated. For example, for the three level system in Figure 7.5 a). we obtain the rate equations of the three level system in analogy to the two-level system

$$\frac{d}{dt}N_2 = -\gamma_{21}N_2 - \sigma_{21}\left(N_2 - N_1\right)I_{ph} + R_p \tag{7.1}$$

$$\frac{d}{dt}N_1 = -\gamma_{10}N_1 + \gamma_{21}N_2 + \sigma_{21}\left(N_2 - N_1\right)I_{ph} \tag{7.2}$$

$$\frac{d}{dt}N_0 = \gamma_{10}N_1 - R_p \tag{7.3}$$

Here, σ_{21} is the cross section for stimulated emission between the levels 2 and 1 and I_{ph} is the photon flux at the transition frequency f_{21}.In most cases, there are any atoms available in the ground state such that optical pumping can never deplete the number of atoms in the ground state N_0. That is why we can assume a constant pump rate R_p. If the relaxation rate γ_{10} is much faster than γ_{21} and the number of possible stimulated emission events that can occur $\sigma_{21}\left(N_2 - N_1\right)I_{ph}$, then we can set $N_1 = 0$ and obtain only a rate equation for the upper laser level

$$\frac{d}{dt}N_2 = -\gamma_{21}\left(N_2 - \frac{R_p}{\gamma_{21}}\right) - \sigma_{21}N_2 \cdot I_{ph}. \tag{7.4}$$

This equation is identical to the equation for the inversion of the two-level system, see Eq.(6.125). Here, $\frac{R_p}{\gamma_{21}}$ is the equilibrium upper state population in the absence of photons, $\gamma_{21} = \frac{1}{\tau_L}$ is the inverse upper state lifetime due to radiative and non radiative processes.

Note, a similar analysis can be done for the three level laser operating according to the scheme shown in Figure 7.5 (b). Then the relaxation rate from level 3 to level 2, which is now the upper laser level has to be fast. But in addition the optical pumping must be so strong that essentially all the ground state levels are depleted. Undepleted groundstate populations would always lead to absorption of laser radiation.

In the following we want to discuss the electronic structure of a few often encountered laser media. A detail description of laser media can be found in [7].

7.3 Types of Lasers

7.3.1 Gas Lasers

Helium-Neon Laser

The HeNe-Laser is the most widely used noble gas laser. Lasing can be achieved at many wavelength 632.8nm (543.5nm, 593.9nm, 611.8nm, 1.1523μm, 1.52μm, 3.3913μm). Pumping is achieved by electrical discharge, see Figure 7.7.

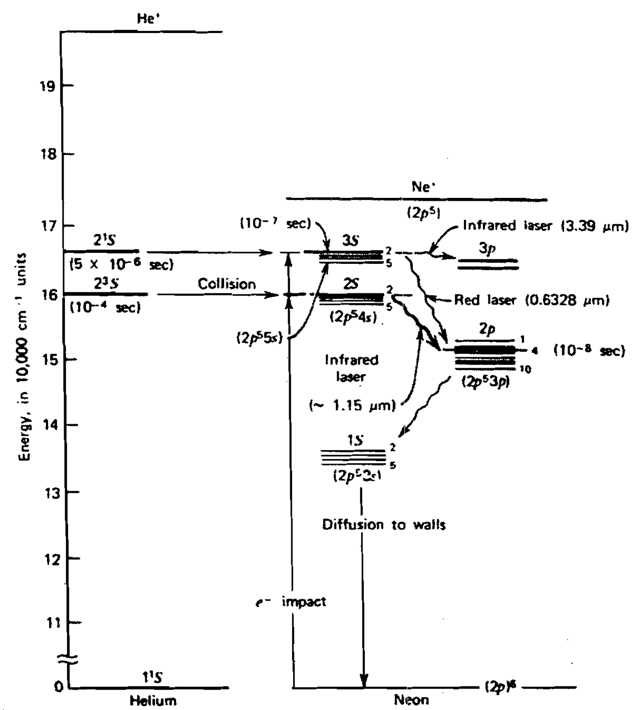

Figure 7.7: Energy level diagram of the transistions involved in the HeNe laser [9].

The helium is excited by electron impact. The energy is then transfered to Neon by collisions. The first HeNe laser operated at the 1.1523μm line [8]. HeNe lasers are used in many applications such as interferometry, holography, spectroscopy, barcode scanning, alignment and optical demonstrations.

Argon and Krypton Ion Lasers

Similar to the HeNe-laser the Argon ion gas laser is pumped by electric discharge and emitts light at wavelength: 488.0nm, 514.5nm, 351nm, 465.8nm, 472.7nm, 528.7nm.It is used in applications ranging from retinal phototherapy for diabetes, 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, 799.3nm. Pumped by electrical discharge. Applications range from scientific research. When mixed with argon it can be used as "white-light" lasers for light shows.

Carbon Lasers

In the carbon dioxide (CO_2) gas laser the laser transistions are related to vibrational-rotational excitations. CO_2 lasers are highly efficient approaching 30%. The main emission wavelengths are 10.6μm and 9.4μm. They are pumped by transverse (high power) or longitudinal (low power) electrical discharge. It is heavily used in the material processing industry for cutting, and welding of steel and in the medical area for surgery.

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

Excimer Lasers:

Chemical lasers emitting in the UV: 193nm (ArF), 248nm (KrF), 308nm (XeCl), 353nm (XeF) excimer (excited dimer). 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 groundstate 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.

7.3.2 Dye Lasers:

The laser gain medium are organic dyes in solution of ethyl, methyl alcohol, glycerol or water. These dyes can be excited by 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 there wide tuning ranges. Unfortunately, dyes are carcinogenic and as soon as tunable solid state laser media became available dye laser became extinct.

7.3.3 Solid-State Lasers

Ruby Laser

The first laser was indeed a solid-state laser: Ruby emitting at 694.3nm [5]. Ruby consists of the naturally formed crystal of aluminum oxide (Al_2O_3) called corundum. In that crystal some of Al^{3+} ions are replaced by Cr^{3+} ions. Its the chromium ions that give Ruby the pinkish color, i.e. its flourescence, which is related to the laser transisitons, see the level structure in Figure 7.8. Ruby is a three level laser.

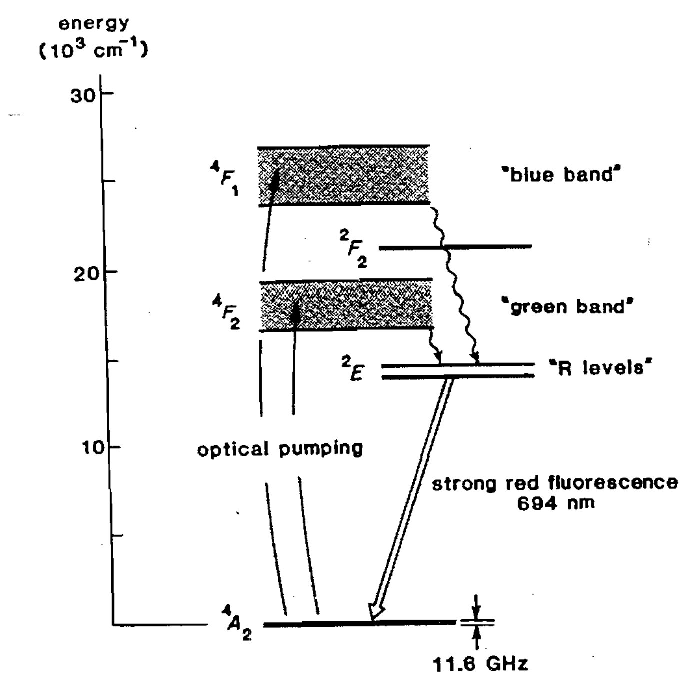

Figure 7.8: Energy level diagram for Ruby, [2], p. 13.

Today, for the manufacturing of ruby as a laser material, artificially grown crystals from molten material which crystalizes in the form of sapphire is used. The liftetime of the upper laser level is 3ms. Pumping is usually achieved with flashlamps, see Figure 7.1.

Neodymium YAG (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, see Figure **??**.

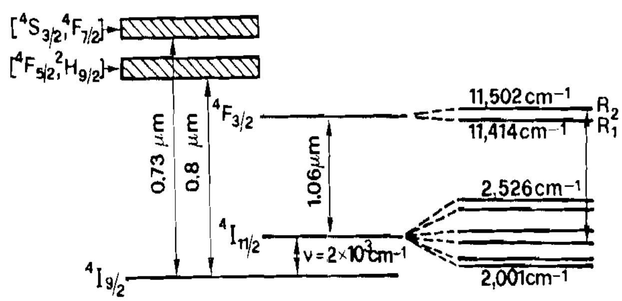

Figure 7.9: Energy level diagram for Nd:YAG, [3], p. 370.

The main emission of Nd:YAG is at 1.064μm. Another line with considerable less gain is at 1.32μm. 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 YLF (Nd:YLF) emitting at 1047μm, YVO4 (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 (Terawatt), high energy (Megajoules) 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 2-3μm range.

Ytterbium YAG (Yb:YAG)

Ytterbium YAG is a quasi three level laser, see Figure 303 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 968nm with laser diodes to provide the high brighness pumping needed to achieve gain.

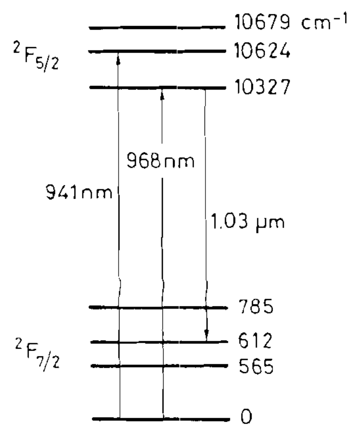

Figure 7.10: Energy level diagram of Yb:YAG, [3], p. 374.

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, $(hf_P - hf_L)/hf_P$ ~ 9%.
- long radiative lifetime of the upper laser level, i.e. much energy can be stored in the crystal.
- high doping levels can be used without upper state lifetime quenching
- broad emission bandwidth of $\Delta f_{FWHM} = 2.5$THz enabling the generation of sub-picosecond pulses

- with cryogenic cooling Yb:YAG becomes a four level laser.

Due to the low quantum defect and the good thermal properties of YAG, Yb:YAG lasers approaching an optical to optical efficiency of 80% and a wall plug efficiency of 40% have been demonstrated.

Titanium Sapphire (Ti:sapphire)

In contrast to Neodymium, which is a rare earth element, Titanium is a transition metal. The Ti^{3+} ions replace a certain fraction of the Al^{3+} ions in sapphire (Al_2O_3). In transistion metal lasers, the laser active electronic states are outer 3s electrons which couple strongly to lattice vibrations. These lattice vibrations lead to strong line broadening. Therefore, Ti:sapphire has an extremely broad amplification linewidth $\Delta f_{FWHM} \approx$ 100THz. Ti:sapphire can provide gain from 650-1080nm. Therefore, this material is used in todays highly-tunable or very short pulse laser systems and amplifiers. Once Ti:sapphire was developed it rapidly replaced the dye laser systems. Figure 7.11 shows the absorption and emission bands of Ti:sapphire for polarization along its optical axis ($\pi-$polarization).

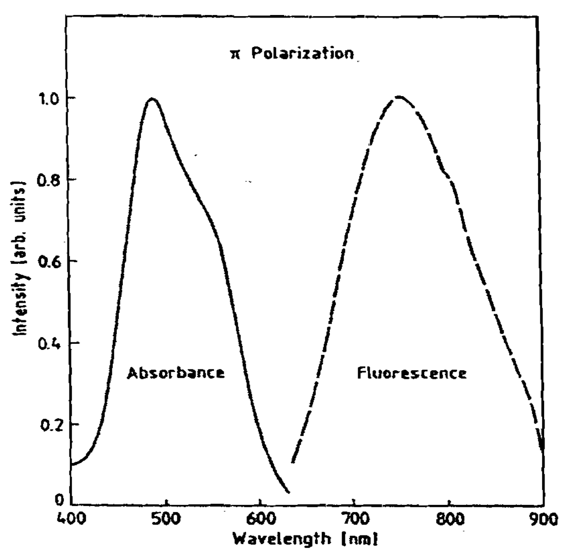

Figure 7.11: Absorption and flourescence spectra of Ti:sapphire, [10]

7.3.4 Semiconductor Lasers

An important class of solid-state lasers are semiconductor lasers. Depending on the semiconductor material used the emission wavelength can be further refined by using bandstructure engineering, 0.4 μm (GaN) or 0.63-1.55 μm (AlGaAs, InGaAs, InGaAsP) or 3-20 μm (lead salt). The 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. In the semiconductor laser the electronic bandstructure is exploited, which arises from the periodic crystal potential, see problem set. The energy eigenstates can be characterized by the periodic crystal quasi momentum vector $\vec{k}$, see Figure

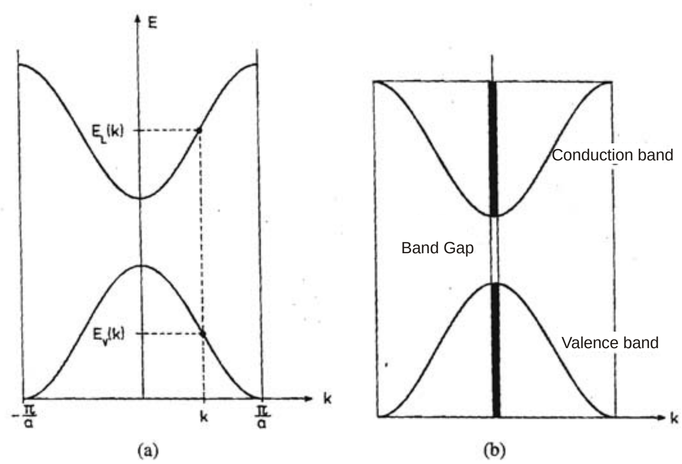

Figure 7.12: (a) Energy level diagram of the electronic states in a crystaline solid-state material. There is usually a highest occupied band, the valence band and a lowest unoccupied band the conduction band. Electronics states in a crystal can usually be characterized by their quasi momentum $\vec{k}$. b) The valence and conduction band are separated by a band gap.

Since the momentum carried along by an optical photon is very small compared to the momentum of the electrons in the crystal lattice, transistions of an electron from the valence band to the conduction band occur essentially vertically, see Figure 7.13 (a).

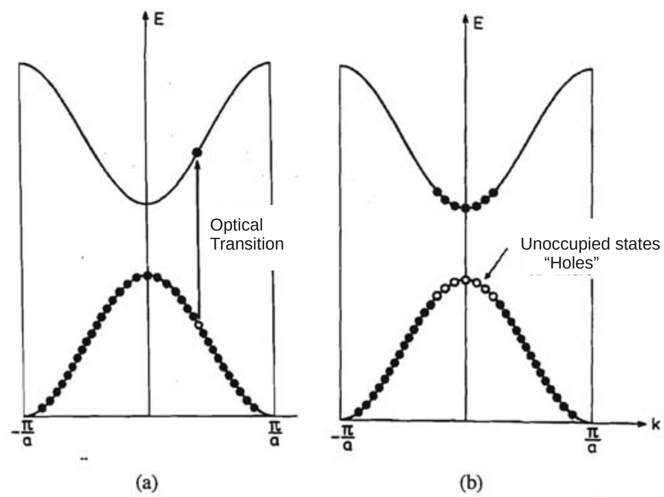

Figure 7.13: (a) At thermal equilibrium the valence band is occupied and the conduction band is unoccupied. Optical transistions occur vertically under momentum conservation, since the photon momentum is negligible compared to the momentum of the electrons. (b) To obtain amplification, the medium must be inverted, i.e. electrones must be accumulated in the conduction band and empty states in the valence band. The missing electron behave as a positively charged particles called holes.

Inversion, i.e. electrons in the conduction band and empty states in the valence band, holes, see Figure 7.13 (b) can be achieved by creating a pn-junction diode and forward biasing, see Figure 7.14.

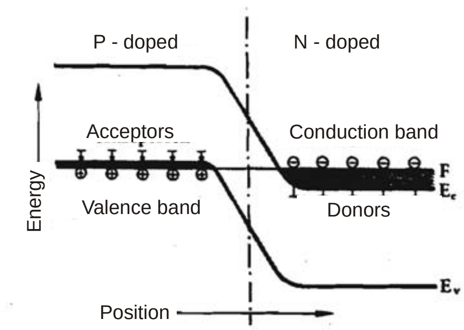

Figure 7.14: Forward biased pn-junction laser diode. Electrons and holes are injected into the space charge region of a pn-junction and emit light by recombination.

When forward-biased electrons and holes are injected into the space charge region. The carriers recombine and emit the released energy in the form of photons with an energy roughly equal to the band gap energy. A sketch of a typical pn-junction diode laser is shown in Figure 7.15.

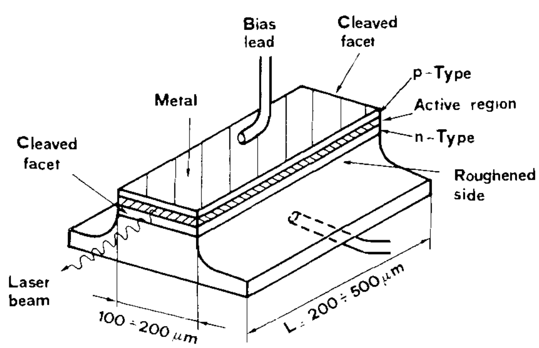

Figure 7.15: Typical broad area pn-homojunction laser, [3], p. 397.

The devices can be further refined by using heterojunctions so that the carriers are precisely confined to the region of the waveguide mode, see Figure

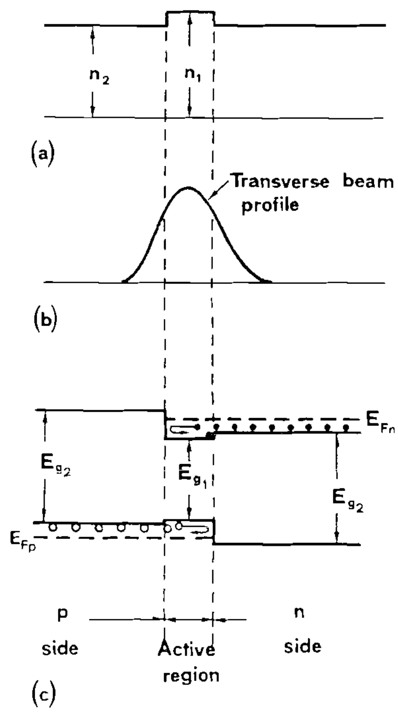

Figure 7.16: a) Refractive index profile. b) transverse beam profile, and c) band structure (shematic) of a double-heterostructure diode laser, [3], p. 399.

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7.3.5 Quantum Cascade Lasers

A new form of semiconductor lasers was predicted in the 70's by the two russian physicists Kazarinov and Suris that is based only on one kind of electrical carriers. These are most often chosen to be electrons because of there higher mobility. This laser is therefore a unipolar device in contrast to the conventional semiconductor laser that uses both electrons and holes. the transitions are intraband transistions. A layout of a quantum cascade laser is shown in Figure 7.17.

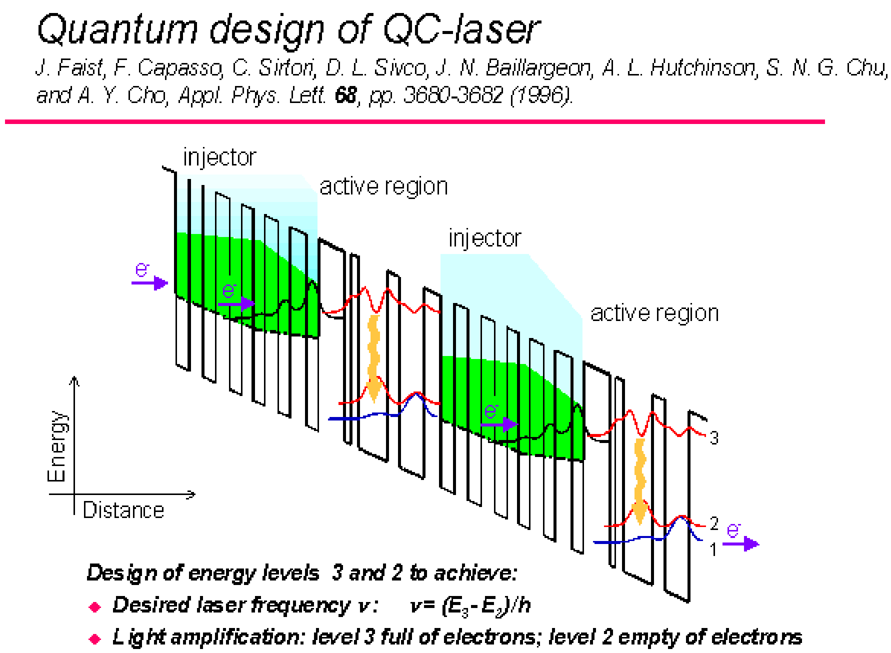

Figure 7.17: Quantum Cascade laser layout.

Like semiconductor lasers these lasers are electrically pumped. The first laser of this type was realized in 1994 by Federico Capasso's group at Bell Laboratories [9], 23 years after the theoretical prediction. The reason for this is the difficult layer growth, that are only possible using advanced semiconductor growth capabilities such as molecular beam epitaxy (MBE) and more recently metal oxide chemical vapor depostion (MOCVD). Lasers have been demostrated in the few THz range [13] up to the 3.5μm region.

Some of the most important spectroscopic parameters of often used laser media are summarized in table 7.1.

7.3.6 Homogeneous and Inhomogeneous Broadening

Laser media are also distinguished by the line broadening mechanisms involved. Very often it is the case that the linewidth observed in the absorption or emission spectrum is not only due to dephasing process that are acting on