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Principles of Lasers

Hans-Jochen Foth

1.1 Introduction

Shortly after their invention, lasers were dubbed 'a solution looking for a problem'. For us, today, this statement sounds totally strange and we may question how this point of view came up. For understanding, it is worthwhile to look closer at the process of the invention of lasers which was an exciting period not only of technological development but also interesting personal interactions.

In 1916, when Albert Einstein published the theoretical basis with his paper on stimulated emission, for many years the technical environment was not advanced enough to make use of it. During the World War II, scientists, especially physicists, worked in several military projects. It was not only in the 'Manhattan Project' to develop the nuclear bomb, but also in projects on radar technology. When the war was over, people with high knowledge in the generation and amplification of microwaves continued their investigations in this field and worked on further improvements. The limitations of classical amplifiers were obvious; in 1951, Charles H. Townes a professor at Columbia University, New York came up with the idea of using gas molecules and stimulated emission. The problem was solved in 1954 by Charles H Townes who, along with James Gordon and Herbert Zeiger, succeeded in the development of 'Microwave Amplification by Stimulated Emission of Radiation', called '*MASER*'. Townes's maser worked with ammonia and was only a pulsed system. The concept for continuous output was first developed by Nikolai Basov and Alexander Prokhorov of the USSR. In 1964, Basov, Prokohorov and Townes shared the Nobel Prize in Physics for developing the maser concept.

Soon after the realization of masers, Townes together with Arthur Schawlow investigated the possibility of optical and infrared (IR) masers. In 1957, Gordon Gould heard about these activities from his wife Ruth who was an assistant professor working on the some floor at Columbia University. Gould was asked by Townes if he could provide information about high-energy lamps. This incited Gould to work hard on his ideas on powerful light emission. At first he wanted to assign a name and decided upon the word 'laser' for 'Light Amplification by

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Stimulated Emission of Radiation' (LASER). He knew how to build a laser by optical pumping and developed a calculation about the output of a laser. Finally, as one of his most important steps, he located a notary public to authorize what he had written and calculated in his notebook. His problem was, that he had only an idea. He needed to construct a working model. In 1958, he abandoned his doctorate and joined a company called Technical Research Group (TRG) to realize his idea.

Gould was aware of strong competition since his brother-in-law Schawlow and Townes were also working on the invention of the laser. In 1958, they both filed a patent and published the first detailed proposal for building an optical maser, which later was renamed as laser. When Gould filed his patent in 1959, it was rejected. But this was not the only bad news for Gould: His company TRG succeeded in receiving $300 000 as research money from the Pentagon for the development of the laser, but the project was classified as a government secret. Because via his wife Ruth, Gould had had contact to the Marxist group and was told to be a supporter, his permission to work on this (his) research project was not improved.

The publication of Townes and Schawlow started the race. Several research groups worked hard to build the first working laser. Townes and two of his Ph.D students worked on a potassium vapor laser but got stuck in technical problems. Schawlow followed the idea of an artificial ruby rod with two similar parallel front sides containing reflection layers to form the resonator. However, he tried to get it working in the IR wavelength range. It was in May 1960 that Theodore Maiman at the Hughes Laboratories in Malibu invented the first working laser. His ruby laser was designed for emission in the red visible range. However, it was only capable for pulsed operation since it is a system involving three energy levels. Continuous operation is achieved more easily by a four level system. This was developed in 1960 by Peter Sorokin and Mirek Stevenson using uranium doped calcium floride. Unfortunately they could not achieve continuous operation. Just before the end of 1960, published in 1961, Ali Javan, William Bennet, and Donald Herriot succeeded in the development of the helium–neon laser as the first gas laser and the first continuous laser. Since atomic gas lasers were limited in power, C. Kumar, in 1964, began developing molecular lasers like the CO_2 laser and the CO laser and could build the first high-powerful lasers. In 1964, Earl Bell worked on the mercury ion laser by placing mercury in helium. Although the mercury laser was not a powerful system and did not have much applications, this type of technology opened the door for the development of the argon–ion laser developed by William Bridge.

The excitement about the application of lasers was as quick to cool down in 1964 as it was when it arose. The outputs of the systems were small. Especially the US government was disillusioned about its application in the military. To succeed in getting financial support the company TRG had coined the word 'death rays'. In this phase of disappointment, lasers were described as 'a solution looking for a problem'. Nevertheless, film makers had great vision: in the James Bond movie 'Gold Finger', which was released in theaters in 1964, a red laser beam is used to cut a thick gold plate and the beam comes dangerously close to the body of Mr Bond, who got clamped to the plate.

In 1981, Schawlow together with Nicolaas Bloembergen was awarded the Nobel Prize 'for their contribution to the development of laser spectroscopy'. What happened to Mr Gould? He had a hard legal battle to fight to show that his ideas would lead to a working laser system. In this trial his authorized notebook was of highest importance. Finally he succeeded and he and his patent-attorneys got royalties till 1994.

1.2 Physical Principles

The name 'LASER' is an acronym, an artificial word, built by the initials of the expression 'Light Amplification by Stimulated Emission of Radiation'. Let us focus onto the different words:

1.2.1 Light

From the standpoint of physicists we have two models to describe the behavior of light. First it is an electromagnetic wave, which may, for example, propagate in x direction.

$$E(\boldsymbol{x}, t) = E_0 \cdot \sin\left(\omega t - kx\right) \tag{1.1}$$

E_0 is the amplitude of the electric field

ω is the rotational frequency with $\omega = 2\pi\nu = 2\pi/T$, where ν is the oscillation frequency and T the oscillation time.

k is called the wave vector; its value is $k = 2\pi/\lambda$ where λ is the wavelength.

The wavelength λ and the oscillation frequency ν are correlated by the speed of light c by:

$$c = \lambda\nu \tag{1.2}$$

The speed of light has the value $299\,792\,458\,\mathrm{m\,s^{-1}}$. Since visible light is in the wavelength range of $\lambda = 400\,\mathrm{nm}$ (blue)–$800\,\mathrm{nm}$ (red), the oscillation frequency of visible light varies from 7.5×10^{14} to 3.75×10^{14} Hz.

The understanding of light as an electromagnetic wave is necessary and sufficient to describe refraction and diffraction while a light beam propagates through different kinds of material. However, this model is inadequate to describe the interaction of light with atomic and molecular systems. For this purpose we need the model of light as a particle beam.

Now, light is described as a flux of photons. Each photon propagates with the speed of light and contains the energy

$$E = h\nu \tag{1.3}$$

where ν is the frequency and h is Planck's constant ($h = 6.675 \times 10^{-31}$ Js).

1.2.2 Amplification

Amplifiers are well known to all of us, since they are in all electronics such as TV set, radio and mobile phone used by us daily. In general, when a signal with a small amplitude is guided onto the input of an amplifier, the signal shows up with several times higher amplitude at the output. Over the years, electronic components built from semiconductors got faster so that carrier frequencies of several gigahertz can be amplified without significant distortion. Nevertheless electronic amplifiers remain inadequate for the amplification of electromagnetic waves with frequencies in the range of 10^{14} Hz. The amplification of the oscillation frequency of visible light needs a totally different physical process – that is, the amplification by stimulated emission of light first described in 1922 by Albert Einstein. Since this is the key word for lasers it is described in a separate paragraph.

1.2.3 Stimulated Emission

Irradiation of atoms or molecules may cause absorption of the light beam. Macroscopically we observe a decrease of the light intensity; in quantum mechanics, the energy of the photons has to fit the gap between energy levels, for example between the levels 1 and 2, with the energy values E_1 and E_2, as shown in Figure 1.1(a), then a part of the population N_1 of level 1 is transferred to the level 2 and builds the population N_2. The transition rate is given by

$$\mathrm{d}N_{\mathrm{absorption}} = N_1 \cdot u(\nu) \cdot B_{12} \cdot \mathrm{d}t \tag{1.4}$$

where $u(\nu)$ represents the power density of the radiation field at the frequency ν, $\mathrm{d}t$ is a small time interval and B_{12} is the Einstein coefficient for the transition from level 1 to level 2.

The energy stored in level 2 by the population N_2 will not stay there forever. Typical lifetimes are in the range of 10^{-8} s in which the energy is re-emitted spontaneously by emitting a photon, see Figure 1.1(b). The transition rate for this spontaneous emission is given by

$$\mathrm{d}N_{\mathrm{spont.emission}} = N_2 \cdot A_{21} \cdot \mathrm{d}t \tag{1.5}$$

A_{21} is the Einstein's coefficient for a spontaneous transition from level 2 to level 1.

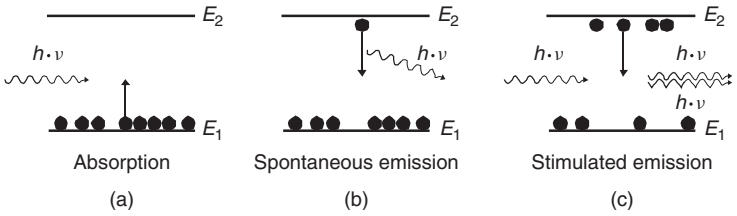

Fig. 1.1 Interaction of light with a two level system.

Since the spontaneous emission is not correlated to the previous absorption, the newly emitted photon can propagate randomly in any direction. Its energy is given by the difference between the energy levels; because these levels are broadened the energy of the emitted photon can differ slightly compared to the absorbed photon. Finally the phase of the electromagnetic wave is random. Macroscopically we observe fluorescence emitted from the atoms in all directions.

As mentioned above, Einstein described an additional process for photon emission. Whenever a photon with the correct energy interacts with an atom (or molecule) in the excited state, the atom is stimulated to jump to the lower level and emit the energy in the form of an additional photon, which is like a twin of the incoming photon (Figure 1.1(c)). Both photons have absolutely the same energy, the same propagation direction and the same phase. The net balance of this process is: one photon plus internal energy gives two identical photons. This is the important amplification process; its transition rate is given by

$$\mathrm{d}N_{\text{stim.emission}} = N_2 \cdot u(\nu) \cdot B_{21} \cdot \mathrm{d}t \tag{1.6}$$

B_{21} is the Einstein's coefficient for the stimulated process from level 2 to level 1.

Macroscopically we observe an exponential increase of the light intensity while the beam propagates through the sample. The segment with the atoms (or molecules) is called *optical amplifier*.

1.2.4
Population Inversion and Enhancement of the Light Field

Obviously a laser system operates correctly when the process of stimulated emission is stronger than the other two processes: absorption and spontaneous emission. How can this be achieved?

1.2.5
Stimulated Emission Stronger than Absorption

When we compare Equation 1.6 with Equation 1.4 we have to postulate

$$N_2 \cdot u(\nu) \cdot B_{21} \cdot \mathrm{d}t > N_1 \cdot u(\nu) \cdot B_{12} \cdot \mathrm{d}t \tag{1.7}$$

The two Einstein coefficients B_{12} and B_{21} differ only by a factor given by the ratio of their multiplicity. For simplicity we set this ratio to one, therefore Equation 1.7 comes to

$$N_2 > N_1$$

which is an abnormal situation for the population of energy levels. In thermal equilibrium the population of levels is described by the Boltzmann's distribution

(E is the energy of the specific level)

$$N(E) \propto e^{-E/kT} \tag{1.8}$$

which tells that levels with higher internal energy are less populated, that is, $N_2 > N_1$. For laser operation we have to bring this correlation upside down. We have to install a *population inversion*; the higher level 2 must be more populated than the lower level 1. Since this situation does not exist in nature under thermal equilibrium, it has to be generated under the input of energy.

Population inversion cannot be achieved for a two level system under continuous irradiation. Three or four level systems are needed, with a long lifetime of the upper laser level.

1.2.6
Stimulated Emission Stronger than Spontaneous Emission

Now we have to compare Equation 1.6 with Equation 1.5

$$N_2 \cdot u(\nu) \cdot B_{21} \cdot dt > N_2 \cdot A_{21} \cdot dt \tag{1.9}$$

which simplifies to

$$u(\nu) \cdot B_{21} > A_{21} \tag{1.10}$$

However, the ratio of the two Einstein coefficients for stimulated and spontaneous processes depends on the frequency

$$\frac{A}{B} \propto \nu^3 = \frac{c^3}{\lambda^3} \tag{1.11}$$

The shorter the wavelength λ of the laser transition is, the harder one has to work so that stimulated emission beats spontaneous emission. Going from red light at 800 nm to blue light at 400 nm induces eight times more effort. The ratio cited in Equation 1.11 is the reason why amplification by stimulated emission was first achieved with microwaves, called *MASER*, and only years later in the visible wavelength range.

The only chance to fulfill the condition of Equation 1.10 is to apply a very strong light field $u(\nu)$, which means, that the emitted photons should not be allowed to escape. Hence an arrangement of mirrors is installed, called *optical resonator*, and the optical amplifier is placed inside of the optical resonator.

1.2.7
Laser Threshold

Figure 1.2 shows schematically the start of the laser process. Part (a) shows in the center of the optical resonator the optical amplifier, which is charged with energy. As

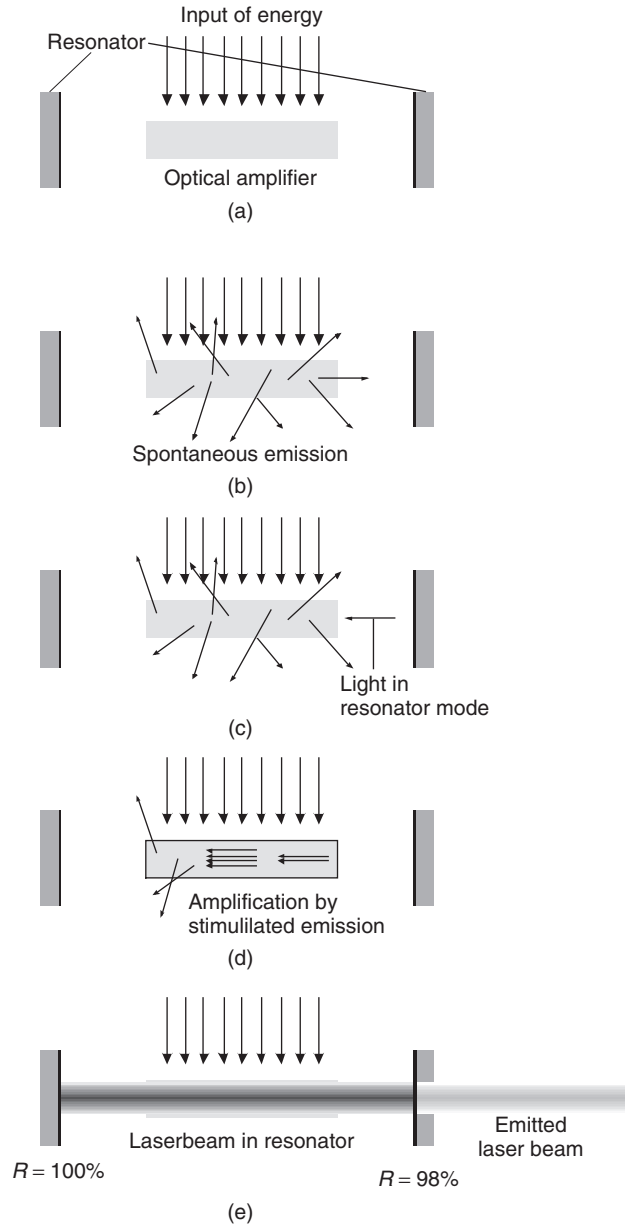

Fig. 1.2 Principle of a laser.

soon as some atoms are excited into the upper levels, spontaneous emission starts emitting fluorescence photons in various directions (Figure 1.2(b)). Assume one photon propagates to the right exactly along the optical axis of the resonator; it will be reflected on the mirror back (see Figure 1.2(c)) into the optical amplifier where it interacts with atoms in the excited states. Stimulated emission yields the number of photons in this propagation direction from 1 to 2 to 4 to 8 to 16 and so on as shown in Figure 1.2(d). The number of photons in this direction grows exponentially with the propagation length in the optical amplifier (as long as no saturation occurs). The beam exits the amplifier at the left side, gets reflected by the left mirror and propagates back in the optical amplifier. Therefore a strong light beam builds up, which bounces back and forth between the two mirrors. The mirror shown on the left side in Figure 1.2(e) has an almost 100% reflectivity and is therefore called *high reflector*, while the mirror shown on the right side, called out coupler, has slight transmission, for example 2%. In this case 2% of the resonator internal beam intensity is coupled to the outside and used for experiments or material processing. A much higher intensity remains in the resonator to ensure that stimulated emission is stronger than spontaneous emission.

In reality the system is more complicated than the brief description given here. The transmission through the output coupler mirror is a wanted loss of photons. However, even under the best conditions there are always additional losses due to scattering and absorption in various optical components. The system starts with laser operation only when the net gain is larger than the sum of all losses. Figure 1.3 shows the population inversion ΔN versus the pump rate R. With increasing pump rate ΔN increases as long as the laser process has not started. At a specific threshold R_C the net gain is larger than the sum of all losses, hence stimulated emission becomes the strongest process and decreases the population inversion. Therefore, for $R > R_C$ the population inversion remains constant on the level N_C. Stronger pumping gives yields to photons emitted in the direction of the laser beam, which is displayed by the dashed line in Figure 1.3.

1.2.8
Resonator Modes

The optical resonator, that is the arrangements of mirrors, which are placed around the optical amplifier, has a strong impact on the electromagnetic wave

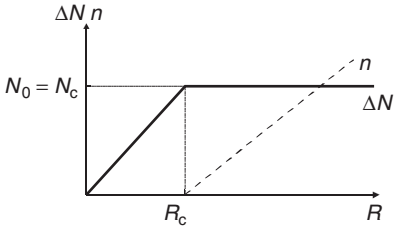

Fig. 1.3 Population inversion ΔN and number of emitted photons n versus pump rate R.

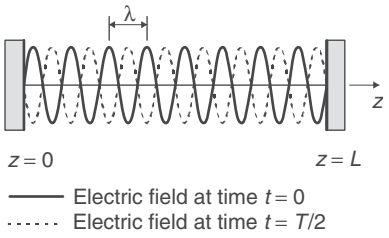

Fig. 1.4 Electric field strength in a resonator; solid line at time $t = 0$, dashed line at the time of $T/2$ later, where T is the oscillation time of the field (see Equation 1.1).

which is going to buildup during the round trips. The simplest version is just two mirrors, as shown in Figure 1.2 with the high reflector, reflectivity $R = 100\%$ and the output coupler, $R = 98\%$ for example. In principle these can be two flat mirrors. Since the resonator gives boundary conditions, only specific distributions of the electromagnetic field can be established under laser operation. Clearly the electromagnetic wave has to be reproduced after a roundtrip, which leads to the boundary condition that the electric field is zero on the surface of the mirrors as shown in Figure 1.4.

Thus several times of half of the wavelength λ will fit between the mirrors – that is

$$L = q\frac{\lambda}{2} \tag{1.12}$$

The number q can be quite large; for example an He–Ne laser with $L = 30\,\text{cm}$ and $\lambda = 633\,\text{nm}$ gives $q = 947\,867$.

Each q value represents an axial, or called *longitudinal*, mode of the laser resonator. The correlated wavelength λ_q is given by

$$\lambda_q = 2\frac{L}{q} \tag{1.13}$$

With the correlation of frequency ν and wavelength λ given in Equation 1.2 the corresponding resonator frequency ν_q is

$$\nu_q = \frac{c}{\lambda_q} = q\frac{c}{2L} \tag{1.14}$$

The difference between two neighbored longitudinal modes is called free spectral range $\Delta\nu_{\text{FRS}}$ and is given by

$$\Delta\nu_{\text{FSR}} = \nu_{q+1} - \nu_q = \frac{c}{2L} \tag{1.15}$$

Another important spectral range for laser operation is the so-called gain width $\Delta\nu_{\text{gain}}$, in which the gain is above the laser threshold γ_{thr}. Whenever $\nu_{\text{gain}} > \nu_{\text{FSR}}$ more than one longitudinal mode can be amplified, as displayed in Figure 1.5.

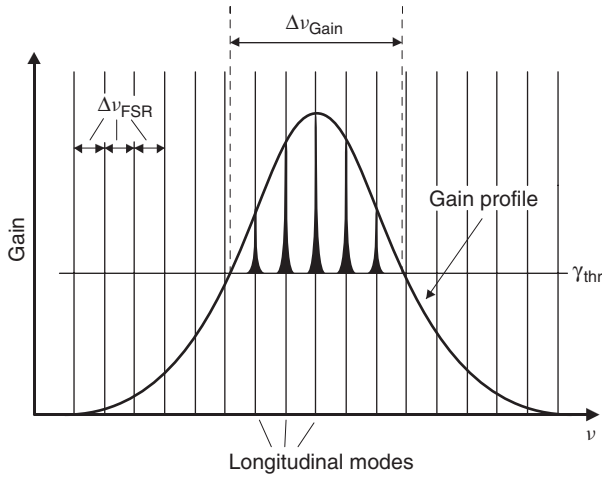

Fig. 1.5 Amplification of more than one longitudinal mode.

As an example, an optical resonator with $L = 50\,\text{cm}$ has a free spectral range of 0.5 GHz. This is for an He–Ne laser smaller than the typical gain width of $\Delta\nu_{gain} = 1.2\,\text{GHz}$, the laser emits not only one wavelength but two or three longitudinal modes. This type of laser operation is called multimode operation. An Ar^+ laser with a resonator length of $L = 1\,\text{m}$ and a gain width of $\Delta\nu_{gain} = 8\,\text{GHz}$ runs on 53 longitudinal modes and a Titan Sapphire-laser up to several million modes.

In the same way as a boundary condition exist along the optical axis (z coordinate), similar conditions exist in vertical direction to the optical axis (x and y coordinate) since the electromagnetic wave has to be zero when the radial size of the mirrors or of the amplifier is reached. This limits the stationary distribution of the electromagnetic field. These modes are called transversal modes. The simplest version is a distribution described by a Gaussian intensity profile. Higher modes have lines of knots, where the intensity is zero. Depending on the number n and m of knots in x and y direction and the number q of knots along the optical axis (see Equation 1.12), the modes are called TEM_{lmq}, where TEM stands for transversal electromagnetic mode. Figure 1.6 shows some examples. It depends on the geometry of the amplifier and the resonator, which types of modes appears and whether they are described by rectangular or cylindrical coordinates. In cylindrical symmetry the mode one order higher than the Gaussian ground mode TEM_{00} is a round mode TEM_{10} with no intensity in the center; it is called Donut mode and generated by losses in the optical components $\Delta\nu_{Gain}$ right on the optical axis.

Whoever has aligned a laser resonator with two flat mirrors knows how critical this resonator is. Both mirrors have to stay absolutely perpendicular to the optical axis; even a tiny tilting angle will stop the laser process. Much easier for alignment

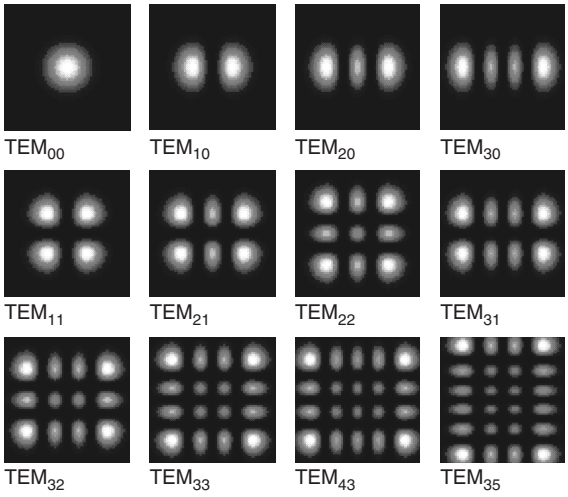

Fig. 1.6 Examples of transversal modes.

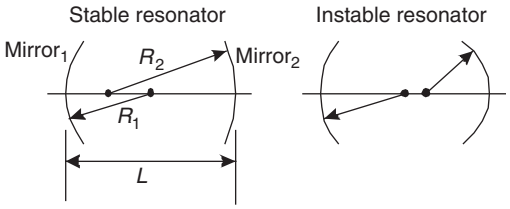

Fig. 1.7 Stable and instable optical resonator.

and insensitive against mechanical distortions are setups with spherical mirrors (Figure 1.7) or, for example, a spherical high reflector and a flat ($R_2 = \infty$) output coupler. Since the electromagnetic wave must be reproduced after a round trip, the resonator length L and the radius of the mirrors R_1 and R_2 have to fulfill the boundary condition

$$0 \leq g_1 \cdot g_2 \leq 1 \tag{1.16}$$

where $g_i = 1 - L/R_i$ for $i = 1$ and 2.

Besides the simple version of an optical resonator built-up by just two mirrors shown in Figure 1.7, more sophisticated setups are used when needed. Figure 1.8 shows examples with tree mirrors to build a so-called folded resonator with a focal point inside the resonator as well as a ring resonator. The longitudinal boundary condition requires that the electromagnetic wave fits to its own tail after one round trip. Thus the condition for a ring resonator with total round trip length L is

$$L = q\lambda \tag{1.17}$$

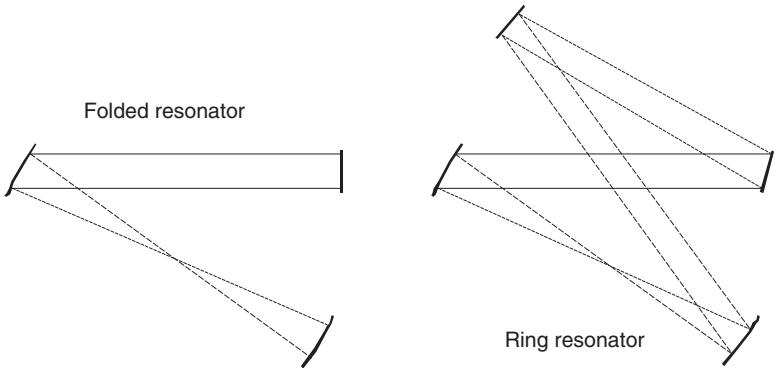

Fig. 1.8 Folded and ring resonator.

1.2.9 Homogenous and Inhomogeneous Broadening

Figure 1.5 shows a broadened gain profile with gain width ν_{gain}. This broadening is caused by various physical effects inducing two different types of broadening: homogeneous and inhomogeneous broadening. The main features of both are listed in Table 1.1 and displayed in Figure 1.9.

1.2.10 Continuous and Pulsed Laser Operation

1.2.10.1 Continuous Wave (cw)

In this mode the laser system emits power almost constantly. The average power P_A and the peak power P_P are identical. Not all laser systems run continuously; often the population inversion can only be achieved for a short time. Therefore, the resulting laser emission is limited to a short time period; the laser runs in a pulsed mode.

Table 1.1 Comparison of homogeneous versus inhomogeneous broadening

Type of Broadening	Physical Reason	Effect on Laser Modes
Homogeneous broadening: the central frequencies ν_c for atoms or molecules are equal	Lifetime broadening, electric fields in a crystal	All modes can be emitted simultaneously.
Inhomogeneous broadening: ensembles of atoms (molecules), each with a different central frequency	Doppler shift due to thermal velocity distribution	Mode hopping and mode competition: (see mode locking, Section 1.2.10.5)

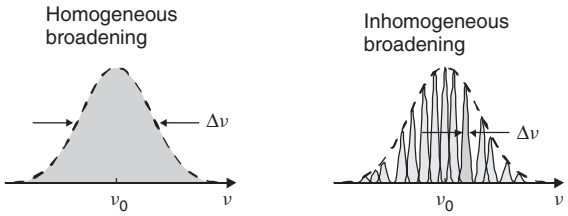

Fig. 1.9 Homogenous and inhomogeneous broadening.

1.2.10.2 **Pulsed Mode**

The simplest version for pulsed laser operation is a time limited pump rate from the ground state. This is performed in gas lasers by a pulsed electric discharge and in all optically pumped lasers by a pulsed discharge lamp. The emitted laser pulse follows the temporal energy input, but starts with a time delay, because at first the population inversion has to reach the laser threshold, and may be shorter because the laser is off as soon as the population inversion is below the threshold. Typical pulse durations of various lasers are: excimer laser: 18 ns, Erbium:YAG: 0.3 ms, CO_2 laser 0.1 s (normal pulse) or $\sim$ 70 µs ('Super Pulse').

1.2.10.3 **Spiking or Pulse Relaxation**

The laser output does not show a smooth time function in all cases. Some laser systems have the tendency for spiking or relaxation oscillations. When the pumping energy rises, the population inversion ΔN increases and will exceed the laser threshold $\Delta N = N_C$. Rapidly, the laser process can start and the stimulated emission will decrease the population inversion ΔN. It is not unlikely that the depletion is stronger than the refill by the pump process. Consequently ΔN will decrease below N_C and the laser process stops. Now depletion of ΔN by stimulated emission is off, but on other hand, excitation by the lamp is strong. Hence the population inversion ΔN raises again, exceeds the threshold N_C and the laser process starts again until the stimulated emission brings ΔN below N_C. These 'on' and 'off' processes can go on for many cycles until the system comes to a stationary process with $\Delta N = N_C$ as shown in Figure 1.3. The laser output shows several strong spikes at the beginning of the pulse. Even when the pulses of relaxation oscillation may be as short as some ns, they are rarely used for applications since it is hard to control them and ensure the same intensity and pulse duration from pulse to pulse. A much better control for short pulses is give by quality switching.

1.2.10.4 **Quality Switching**

The principles of quality switching, short form: Q-switch, are shown in Figure 1.10. Figure 1.10a shows the pump rate caused by the lamp. This profile is followed in principle by the population inversion ΔN (Figure 1.10c). As soon as the laser threshold is reached stimulated emission will become a dominant process. The laser emission will start and keep the population inversion on the level of the threshold $\Delta N = N_C$. The disadvantage: There are no really powerful pulses. Storage of energy is possible when the system is hindered to start when the

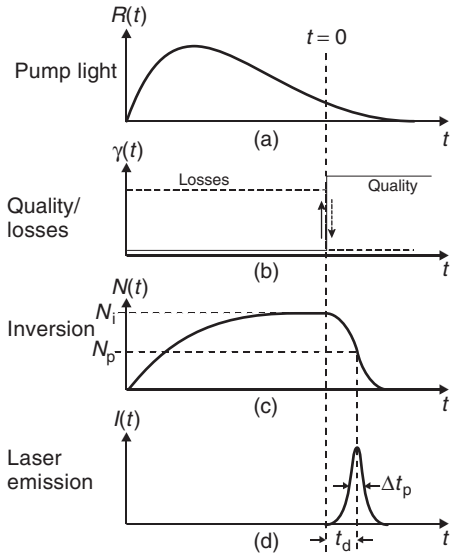

Fig. 1.10 Quality switching.

threshold is reached so that $\Delta N \gg N_C$ is achieved. This is realized technically by interrupting the laser resonator: the quality of the resonator is set to a low value. When the population inversion has reached a high value and may be saturated, the resonator is quickly switched to high quality (shown in Figure 1.10b), which enables the system to start lasing with a huge population inversion and emit a powerful pulse (Figure 1.10d).

Switching the quality of the optical resonator is done mechanically by placing a chopper wheel in the resonator or by rotating a mirror around an axis perpendicular to the laser axis or it is done electro optically by rotating the polarization plane by Faraday effect or Kerr effect.

Typical pulse lengths are in the range of 10^{-6} s (μs)–10^{-9} s (ns):

1.2.10.5 **Mode Locking**

In the case of inhomogeneous broadening all modes that are above the threshold, start in an uncorrelated way. Whenever a mode starts, it decreases its population inversion and its gain. Because the other competitive modes are inactive, they remain on high-population inversions and high gains. One of them will finally be the winner and overcome the previous mode. However, after a short time its gain is decreased, which is an advantage for the first or other modes. Laser operation jumps chaotically from one mode to another; thus the output frequency (resp. wavelength) of the laser also jumps chaotically between various values within the gain width.

With various methods the modes can be locked together and forced to a coordinated operation. Mode locking can be achieved passively, for example by a

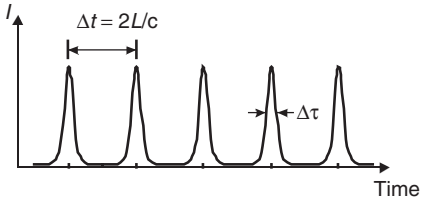

Fig. 1.11 Laser emission under mode locking.

saturable absorber within the optical resonator or can be performed in an active process, for example by an opto-acoustic modulator, which generates pressure waves with the modulation frequency ν_{mod} induced in a quartz crystal to generate side bands at $\nu_q - \nu_{\text{mod}}$ and $\nu_q + \nu_{\text{mod}}$ to the frequency of the resonator mode ν_q. When the modulation frequency is equal to the free spectral range ν_{FSR} of the resonator (see Equation 1.15)

$$\nu_{\text{mod}} = \nu_{\text{FSR}} \tag{1.18}$$

all modes are locked. Assume one mode q starts, then the sidebands match to the frequencies of the neighbor modes $q + 1$ and $q - 1$ and will force them to start lasing with exactly the same phase. The sidebands of the neighbor modes $q + 1$ and $q - 1$ are in resonance to the alternate neighbors $q + 2$ and $q - 2$, so also the emission of these modes is locked. Finally all modes above the threshold (as shown in Figure 1.5) are locked. The laser emission is the superposition of all contributing modes and has the shape of a thin disk of light, which travels back and forth between the two mirrors of the optical resonator. Its time dependence is shown in Figure 1.11; the time separation between the pulses is

$$\Delta t = 2L/c$$

(with $L =$ length of the resonator and $c =$ speed of light). This value is the so-called resonator round trip time, that is the time which an electromagnetic wave needs to travel from the output coupler to the high reflector and back to the output coupler. The time duration of each pulse gets shorter, the more modes are coupled; the mathematical description of this interference of various longitudinal modes is very similar to scattering of a wave on a grating. Under optimal alignment the pulse duration is the reciprocal of the frequency gain width

$$\Delta\tau = 1/\Delta\nu_{\text{gain}}$$

The gain width of an Ar^+ laser with $\Delta\nu_{\text{gain}} = 8\,\text{GHz}$ gives $\Delta t = 0.125\,\text{ns}$, while a Kerr lens mode locked TiSa laser can have a bandwidth up to $\Delta\nu_{\text{gain}} = 128\,\text{THz}$ (with a central wavelength of $\lambda = 800\,\text{nm}$, the wavelength bandwidth is $\Delta\lambda = 300\,\text{nm}$) and gives pulses of almost 8 fs ($1\,\text{fs} = 10^{-15}\,\text{s}$) length.

1.3
Technical Realization

Since the first working laser system was a solid-state laser, this chapter will start with the description of solid-state lasers and then proceed with gas lasers, liquid lasers and semiconductor lasers. At the end of the chapter frequency doubling and other nonlinear manipulations are described.

1.3.1
Solid-State Lasers

The first laser built in 1960 by Th. Maiman was a ruby laser. The optical amplifier was a ruby crystal (0.05% Cr in a pure Sapphire Al_2O_3 crystal) formed to a rod and pumped optically by helically formed discharge lamp, which surrounded the ruby crystal. Lamp and crystal were placed in an optical cavity with an inner reflecting surface, to increase the efficiency with which the photons emitted by the lamp are absorbed in the laser crystal. The optical resonator was formed by the crystal's front and end surfaces, which was precisely polished and coated. Basics of this concept were used for a long time to build solid-state lasers, as shown in the setup in Figure 1.12. Most setups used cylindrical discharge lamps, mounted parallel to the laser rod inside of the cavity. The cavity can have a circular cross-section and reflecting or scattering inner surface or it has an elliptical cross-section and high-reflecting inner surface. For stronger optical pumping arrangements with two and four pumping lamps had also been developed.

For several decades the laser system built-in highest production numbers was the Nd:YAG laser. 'Nd' stands for the chemical element Neodymium, as the laser medium and 'YAG' for Yttrium Aluminum Granate, which is the host crystal. The emitted wavelength is mainly determined by the laser medium, that is, by the energy levels of the Cr^{3+} ions embedded in the YAG crystal; however, since the electric and magnetic fields of the crystal can change the energy levels, the host

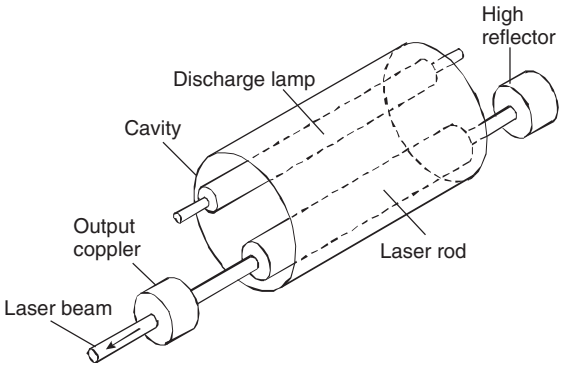

Fig. 1.12 Principle setup of a solid-state laser.

Table 1.2 Examples of solid-state lasers

Material	Wavelength	Pulse Width	Power
Ruby	694.3 nm	0.5 ms–30 ps	1 GW
Nd/Glas	1064 nm	20 ns–5 ps	10 GW
Nd/YAG	1064 nm	CW	15 W
		5 ms–20 ps	1 GW
Diode	0.8–32 µm	CW	200 mW
Array structure	–	CW	8 W
Array structure	–	150 µs	134 W
Color center	0.8–3.2 µm	CW	2,7 W
Alexandrite	720–800 nm	CW	4,5 W
		30–0.1 ms	5 mW
Titan/Sapphire-Laser	680–1000 nm	CW	3.5 W
Erbium/YAG	2.94 µm	CW	2 W
		250 µs	8 kW
Holmium/YAG[a]	2.1 µm	CW	0.8 W

a The exact description is Ho:Cr:Tm:YAG: Holmium is the laser medium, YAG the host crystal, Chromium and Thulium are added to improve the absorption of pump photons and the energy transfer to the upper laser level in Holmium.

crystal influences the lifetime and the energy of the levels of the laser medium. This influence is the reason why a variety of other host crystals is used regarding the specific laser specification: Nd:Glass, Nd:YSSG, Nd:YLF.

Table 1.2 shows the emission wavelength of various solid-state lasers. The power values are listed for commercial systems; high-sophisticated laboratory systems are significantly stronger.

Although it has been 47 years since the success of the first solid-state laser, the technical development of solid-state lasers is an ongoing process. Recent developments are dealt with in the following text.

1.3.1.1 **Slab Laser**

The laser medium does not have the shape of a rod but of a slab (Figure 1.13). The advantage is seen in a better cooling of the crystal and the breaking of the cylindrical symmetry to avoid heat-induced lens effects.

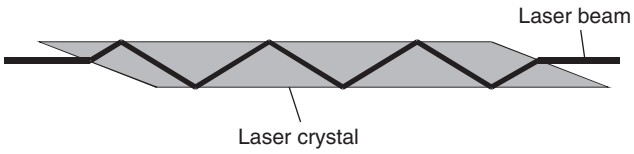

Fig. 1.13 Slab laser.

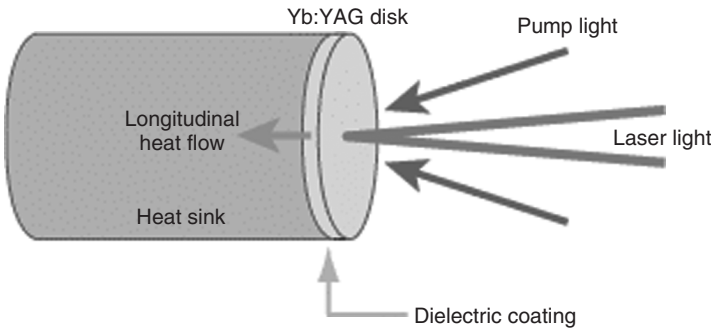

Fig. 1.14 Principle of a disk laser.

1.3.1.2 **Disk Laser**

In a disk laser, the laser crystal is a thin disk, with a thickness considerably smaller than the laser beam diameter as shown in Figure 1.14. Cooling is achieved dominantly through one end face, that is, in the longitudinal rather than in the transverse direction. The cooled end face has a dielectric coating, which reflects both the laser radiation and the pump radiation. Systems with power of 8 kW for metal cutting and welding are commercially available.

1.3.1.3 **Fiber Lasers**

Fiber lasers are usually lasers with optical fibers as gain media (Figure 1.15). In most cases, the gain medium is a fiber doped with rare-earth ions, such as erbium (Er^{3+}), neodymium (Nd^{3+}), ytterbium (Yb^{3+}), thulium (Tm^{3+}) or praseodymium (Pr^{3+}). Pumping is performed by one or several laser diodes, where the pump light is coupled coaxially or by spliced fibers. Since in some systems the fibers are single mode fibers, the laser is forced to TEM_{00} transversal mode. Commercially available systems have powers up to 50 kW cw.

1.3.2 **Gas Lasers**

Most gas lasers consist of a gas sealed glass or quartz tube containing the laser gas which is excited by an electric discharge. Often a magnetic field collinear to the optical axis forces the electrons of the discharge onto helical pathways,

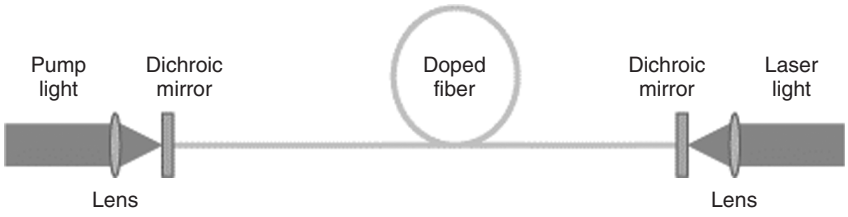

Fig. 1.15 Fiber laser.

which increases to total penetration length in the gas and thereby the efficiency for the energy transfer: kinetic energy of electrons to internal energy of gas particles. In several cases also gas mixtures are used for a more efficient energy transfer.

1.3.2.1 He–Ne Laser

In an He–Ne laser, Helium is excited by electron collision to the 2^1S and 2^3S levels; the excitation energy is transferred by atomic collisions to Neon to populate the 5s and 4s levels. The 5s level for example is the upper laser level for the emission of 3.391 µm line (transition to 4p), of the 543-nm line (green, to lower fine structure levels of 3p) and 632.8-nm line (red, to higher fine structure levels of 3p). All lower laser levels depopulate, mainly by emission of fluorescence, to the 3s level of Neon. The transition from 3s back to the ground state ($1s^2 2s^2 2p^6$) is forbidden for dipole transition. Without depopulation of the 3s state, the lower laser levels would not be depopulated destroying the population inversion between upper and lower laser levels. This problem is technically solved by an inner glass tube in the laser tube, which has a small inner diameter and a thick wall. Neon atoms in the 3s level have to interact with the glass wall to return into the ground state.

The energy transfers described above for the He–Ne laser and the problem of depletion of the lower laser level are common also for several other gas laser systems: Only a small portion of the primary excitation energy is converted into energy of laser photons. The main part of the input energy is converted into energy of fluorescence photons and heat. Depopulation of lower laser levels is a bottle-neck for higher power. Depending on the laser medium, several laser lines can be emitted. Usually one or two transitions have the highest gain and use up the population inversion. Wavelength selective elements, like grating or a prism, are installed in the optical resonator to increase the losses for unwanted transitions. In this way only one wavelength is selected and by tuning this optical element, the laser emission can be switched from one wavelength to another. Figure 1.16 shows the variety of wavelengths available in an Ar^+ laser (Argon–ion laser).

Some of the lasers in Table 1.3 are described briefly in the following text.

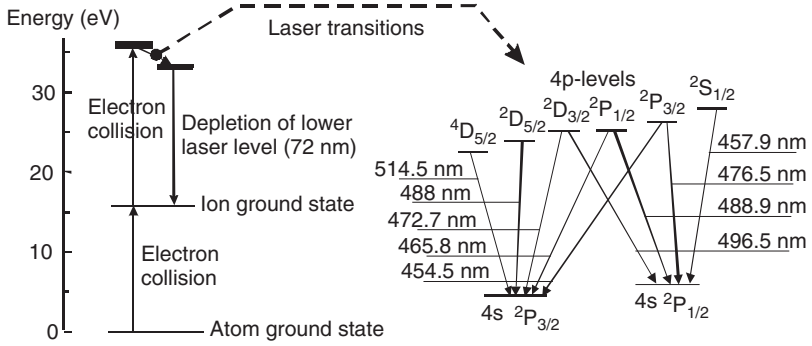

Fig. 1.16 Transitions in Ar^+ laser.

Table 1.3 List of the most popular gas lasers

Kind of Gas	Wavelength	Pulse Width[1)]	Power[2)]
CH_3F	496 µm	CW	100 mW
		40 ns	1 mW
Chemical laser – that is HF	2.7–2.9 µm	CW	7 kW
		20 ns	1 mW
CO_2	10.6 µm,	CW	100 kW
	9–11 µm	100 ps–0.1 s	100 W–1 TW
CO	5–7 µm	CW	20 W
Nobel gas ion laser Ar^+, Kr^+, Xe^+	400–800 nm	CW	25 W
Excimer laser	170–352 nm	15–300 ns	20 mW
He–Ne	543 nm,	CW	50 mW
	632.8 nm,		
	1.152 µm,		
	3.39 µm		
He–Cd	325 nm,	CW	150 mW
	441.6 nm		
H_2	116–160 nm	0.5 ns	5 kW
HCN	311 µm,	CW	40 mW
	337 µm	40 ns	1 mW
Metal vapor copper, gold	325–653 nm	CW	15 mW
		100 ns	5 W
N_2	337.1 nm	0.1–10 ns	1 mW

[1)] and [2)]: Values for commercial systems, specialized Laser systems can emit higher output.

1.3.2.2 CO_2 Laser

Often a mixture of CO_2 and N_2 is used to increase the efficiency for the discharge excitation. The laser transitions take place between various vibrational modes of the CO_2 molecule. The dominant line is at 10.6 µm, and a second line is at 9.6 µm. In most systems the electric discharge runs longitudinal (along the optical axis); however excitation of CO_2 can also be achieved by **t**ransverse **e**lectrical discharge at **a**tmospheric pressure, which is known as TEA laser.

1.3.2.3 Chemical Lasers

The reactants are often formed in a discharge and guided into a reaction chamber. Laser emission is usually perpendicular to the gas flow in the reaction chamber. Population inversion is achieved directly since the chemical reaction generates the final molecules not in the ground state but in excited states. For example, the reaction $F + H_2 \rightarrow HF^* + H$ leads to a population of the vibrational modes of HF^* in $\nu = 0 : 1 : 2 : 3$ in the ratio 1 : 2 : 10 : 5 while the reaction laser $H + F_2 \rightarrow HF^* + F$ generates HF^* in the vibrational modes $\nu = 0$–10 in the ratio 6 : 6 : 9 : 16 : 20 : 33 : 30 : 16 : 9 : 6 : 6. Laser transition takes place between vibronic levels of HF.

1.3.2.4 Excimer Laser

The word 'excimer' is an acronym for 'excited dimer'. Laser medium are molecules that do not exist in the electronic ground state, and are usually a combination of noble gas atom and a halide atom. With both atoms in the electronic ground state, the interaction is described by weak van-der-Waals forces, leading to a purely repulsive potential or a very shallow binding potential. Excitation by electron collision brings one valence electron of the noble gas atom into an s state in an excited shell. The high-electron affinity of the ground state halide atom leads to a negatively charged halide and a positively charged noble gas ion; the Coulomb attraction between both ions generates a deep potential minimum. Formation of molecules in this excited state guides them by vibrational relaxation to the lowest vibrational mode, from where the transition to the ground state occurs. Since the ground state is almost repulsive (the molecule dissociates), no population exists in the ground state and any generation of molecules in the excited state is identical to population inversion.

Table 1.4 shows a summary of excimer lasers. The advantage of these systems is the emission in the ultraviolet (UV) spectral range; the photon energy is high enough to induce direct dissociation in many organic molecules.

1.3.2.5 Metal Vapor Lasers

The vapor pressure is achieved by an oven (250–350° C) close to the anode of the discharge. The vapor diffuses into the small capillary of the discharge tube. Close to cathode is a condensation trap to avoid inner coating of the end windows of the tube. Excitation of the metal atoms is by excited He atoms comparable to the He–Ne laser. The most common metal vapor laser is the copper vapor laser; but systems with Lead, Calcium, Gold, Manganese, Selenium, Thallium and Indium are also working. Owing to the high number of excited states, several emission lines from the IR to the UV wavelength range are available.

1.3.2.6 Nuclear Pumped Lasers

Nuclear pumped laser are lasers pumped with the energy of fission fragments. Some examples for these lasers are CO_2, ^{3}Helium–Argon, ^{3}Helium–Krypton and

Table 1.4 Excimer lasers

Laser Medium	F_2	ArF	KrCl	KrF	XeCl	XeF
Wavelength (nm)	157	193	222	248	308	351
Pulse energie (mJ)[a]	5	200	35	250	150	80
Mean power (W)[a]	0.03	20	4.5	45	25	15

a These values depend on the size of the system. The given values are due to models of medium size. Commercially available systems come up to 160 W.

^{3}Helium–Xenon. The lasing medium is enclosed in a tube lined with uranium-235. The fission fragments of the uranium create excited plasma with inverse population of energy levels. Other methods, for example, the He–Ar laser, can use the He(n,p)H reaction, the transmutation of helium-3 in a neutron flux, as the energy source or employing the energy of the alpha particles. The advantage of this technology is seen in high-excitation rates with small laser volumes.

1.3.3 Dye Lasers

Dye lasers use optically active dyes dissolved in a liquid. Depending on the wavelength range various dyes are used: scintillator dyes (320–410 nm), coumarins (410–560 nm), rhodamins (560–640 nm) and cyanines (640–900 nm). The advantages of dye lasers are that any wavelength between 320 and 1000 nm can be produced and that wavelength tuning is possible over a range of several 10 nm. The disadvantages are that one needs more than one dye for long wavelength scans and that the dye molecules absorb their own laser light. As mentioned at the beginning of this chapter, each laser absorbs its own light; in dye lasers however this problem is worse. Excitation is done by high-power light sources, such as discharge lamps or lasers. The pump wavelength is always shorter than the fluorescence wavelength; due to the Franck–Condon principle the fluorescence transition ends in higher vibrational levels of the electronic ground state. Stimulated emission and laser amplification is also in the wavelength range of the fluorescence. Excitation and re-emission take place between the electronic singlet states. By inner molecular energy transfer population from the excited singlet state can leak to the lowest triplet state from where laser photons are absorbed to excite higher states in the triplet system. This self absorption in the triplet system limits dominantly the output of dye lasers. Technical solutions are additives for triplet quenching, or pulse mode operation and/or pumping systems, which permanently deliver molecules in the singlet system and extract molecules in the triplet system from the optical amplifier. The most highly sophisticated systems use free dye jets, into which the optical pump beam is focused; the optical resonator is a folded or ring resonator (see Figure 1.8), which is setup perpendicularly to the jet stream and which contains wavelength dispersive elements to narrow the bandwidth and to force the system to single mode operation.

1.3.4 Semiconductor Lasers

The most common and practical types of semiconductor lasers are bipolar devices, diodes, formed from a p–n junction and powered by an electric current. Semiconductor materials can be doped to conducted positive charge carriers, holes or negative charge carriers, electrons. Without an externally applied voltage the charge carriers close to the junction combine leaving a depleted layer without electric conductivity. When holes are injected into the p-doped side (the electrons are removed

by a positive voltage) and electrons are injected into the n-doped side, the charge carriers combine in the p–n junction. Semiconductor materials normally used for electronic circuits have such an atomic structure that the recombination of the charge carriers emit phonons, that is lattice vibrations are excited. Other semiconductor materials, like combinations of III–V elements are so-called 'direct band gap' semiconductors in which the recombination of charge carriers emits photons (as used for light emitting diode (LED)). Examples of compound semiconductors are gallium arsenide, indium phosphide, gallium antimonide and gallium nitride. As in all lasers the emission of photons has to be increased to a level for stimulated emission. The optical resonator is usually formed by the cleaved front and end surface of the semiconductor crystal. The index of refraction of the semiconductor material is so high that the reflections on the front and back surface work like mirrors even without specific coatings.

In the beginning of diode laser development the current density of the laser threshold was above 50 000 A cm^{-2}. The solution was the setup of so-called hetero structures, layers of the same type of material but different content of components; for example different content of aluminum in $Al_xGa_{1-x}As$. When these hetero structures were installed on both sides of the recombination layer, as so-called double hetero structure, the current density of the laser threshold could be dropped to 1.600 A cm^{-2}. Figure 1.17 shows the typical setup of a diode laser with a double heterostructure. Top and bottom have a metal layer for electrical contact; before the top metal layer was installed a groove was etched into the isolating oxide layer, which limits the current to a small linear segment. The vertical double heterostructure of GaAs/GaAlAs/GaAs/GaAlAs/GaAs limits the recombination of the charge carriers to a thin layer, central active zone and thus decreases the current threshold for the

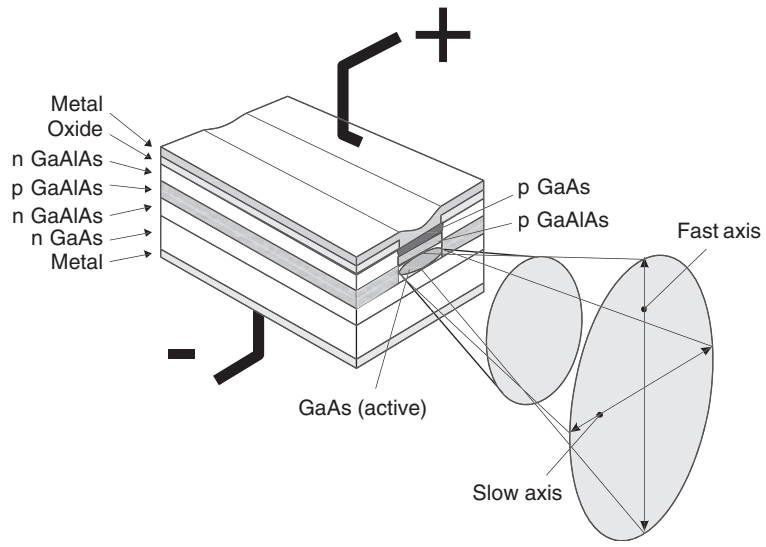

Fig. 1.17 Setup of a GaAs diode laser with diverging light cone.

Table 1.5

Material	Wavelength
GaN	0.4 μm
AlGaAs	0.63–0.9 μm
InGaAsP	1.0–2.1 μm
Lead salt	3–20 μm
Hybrid silicon	Mid-IR

laser process. The active zone is horizontally surrounded by GaAlAs which works like a waveguide for the light field; therefore the whole structure is called 'buried heterostructure'.

Diode lasers have great advantages like high efficiency of ~ 30% for the conversion of electric energy into light energy and of small geometric dimensions. The whole device is in the range of cubic millimeter; the thickness of the active layer, GaAs in Figure 1.17, is only 2 μm-thick and 10-μm wide. However this smallness induces optical problems: due to diffraction the beam cross-section expands rapidly. The vertical divergent angle is large, typically 30°, therefore this direction is called the fast axis, while the lateral divergent angle is smaller, typically 10°, and the direction is called slow axis. The shape of the beam can only be handled by elements of cylindrical optics which contribute significantly to the total costs of the laser system.

Table 1.5 gives a short summary of common material for diode lasers and it wavelengths.

As in other laser systems also diode laser technology is developing rapidly. Some special designs are described below:

Distributed feedback lasers (DFB) do not use discrete mirrors to form the optical cavity; the active region is structured as a diffraction grating by a periodic perturbation in the plane of the active region, which provides optical feedback for the laser due to Bragg scattering. The grating is constructed to reflect only a narrowband of wavelengths and thus shrinks the laser output to a narrow line width. The reflection wavelength of the grating structure and thus the wavelength of the laser output is changed by altering the temperature of the device because the pitch of the grating changes due to thermal expansion. The wavelength tuning range is usually in the order of 6 nm for a ~ 50 K change in temperature. Altering of the modulation rate of the current powering the laser will also tune the wavelength. The emission wavelengths range from 850 to 1500 nm, depending on the material.

Not all setups of diode lasers are in the geometric arrangement as shown in Figure 1.17, with the laser beam emitted in the plane of the layers. The various epitaxial layers can be arranged for a vertical cavity surface emitting laser (VCSEL).

In modern semiconductor lasers very thin layers, so-called quantum films, are used. In quantum well lasers the active layer is shrunken in one direction. As a consequence the variation of the electron's wave function and the corresponding component of the energy are quantized. The density of state functions of electrons has an abrupt edge that concentrates electrons in energy states which contribute to

the laser process. Thus the electric pumping of the laser is much more efficient: current threshold in bulk system: 50 mA versus 1 mA in a quantum well laser. Shrinking the layer's thickness in 2Ds leads to quantum wire lasers, and in 3Ds to quantum dot lasers.

While typical interband semiconductor lasers emit electromagnetic radiation through the recombination of electron–hole pairs across the material band gap, quantum cascade lasers (QCL) are unipolar and laser emission is achieved through electron transitions within the conduction band of a semiconductor.

1.3.5
Free-Electron Laser

Radiation in a free-electron laser (FEL) is generated by the acceleration of a beam of relativistic electrons through a periodic, transverse magnetic field. Two arrays of alternating magnets called undulator or 'wiggler' force the electrons in the beam on a sinusoidal path – that is accelerates them back and forth perpendicularly to the beam direction which results in the emission of photons (see Figure 1.18). Since the electron motion is in phase with the field of the light already emitted, the superposition of all emitted fields produces a coherent light field. The wavelength of the light emitted can be readily tuned by adjusting the energy of the electron beam or the magnetic field strength of the undulators.

FELs have a high value for the generation of collimated high-power x-rays. The systems need long undulators since the principle of amplification lies in so-called self-amplified stimulated-emission free-electron laser (SASE-FEL) which leads to micro bunching of the electrons. The initially equal distribution of all electrons is changed by the interaction of the oscillating electrons with the emitted radiation. The electrons drift into microbunches separated by a distance equal to one wavelength of the radiation. Now the motion of the electrons and the light field are in perfect agreement which leads to the high intensities and the laser-like properties. Examples of facilities operating on the SASE-FEL principle include the free electron laser in Hamburg (FLASH), the Linac Coherent Light Source (LCLS), currently being built at the Stanford Linear Accelerator, and the European x-ray FEL.

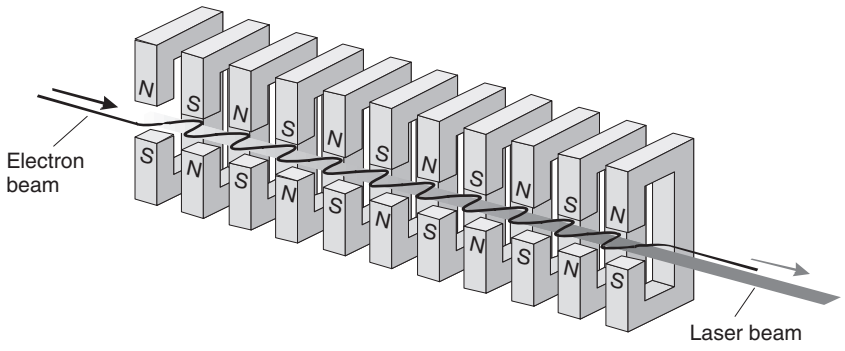

Fig. 1.18 Principle of free-electron laser.

1.3.6
Optical Parametric Oscillator

An optical parametric oscillator (OPO) is a parametric oscillator which oscillates at optical frequencies. A powerful laser beam with the light frequency ν_1, called pump beam, is guided into a nonlinear crystal and excites transitions from the ground state 0 to the state 1 (see Figure 1.19). The transition back is performed by two steps emitting photons with two different frequencies ν_1 and ν_2. These two waves are called 'signal' and 'idler' wave. The three frequencies have to fulfill the boundary conditions:

- Energy conservation: $h\,\nu_1 = h\,\nu_2 + h\,\nu_3$, which gives $\nu_1 = \nu_2 + \nu_3$ and
- Conservation of momentum: $p_1 = p_2 + p_3$

The momentum p of a photon depends on the wavelength λ, $p = h/\lambda$, and λ depends on the index of refraction n. Since in anisoptropic crystals the index of refraction depends on the direction of light propagation regarding to the optical axis, the momentum of a photon is correlated to its propagation in the crystal. Finally conservation of energy and of momentum are only fulfilled for one combination of ν_1 and ν_2. The ratio of ν_1 and ν_2 can be tuned by turning the crystal vertically to the light propagation.

1.3.7
Frequency Doubling and Generation of Higher Harmonics

Frequency doubling or second harmonic generation (SHG) can be easily described in the model of photons: Two photons, each with energy $E_1 = h\nu_1$ are absorbed and excite the system from level 0 to level 1. When the emission path from level 1 to 0 is done in one step, as shown in Figure 1.19 right part, it generates a photon with

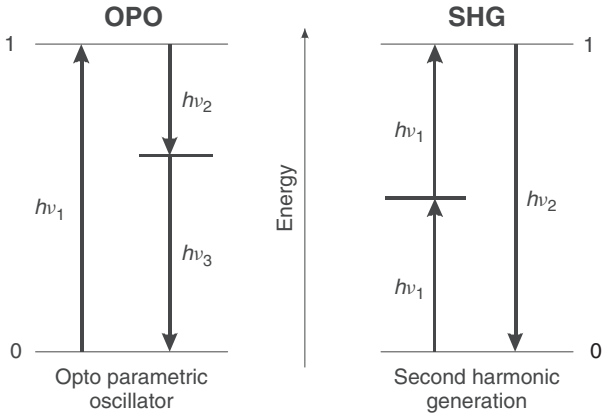

Fig. 1.19 Energy transitions in a OPO and for SHG.

the energy $E_2 = h\,\nu_2 = 2\,h\,\nu_1$ – that is the emitted wave has the double frequency respectively its wavelength λ_2 is half of the irradiated wavelength λ_1.

Some of the technical problems in the realization of frequency doubling can be better explained in the wave picture: An electromagnetic wave interacting with an atom induces the electron cloud to oscillate against the nucleus. The emission of the system can be described as an Hertz oscillator. As long as the electric field is small, the polarization P of the atomic system is proportional to the field E.

$$P(\nu) = aE(\nu)$$

The situation changes when a powerful laser beam is applied. Now the electric field may be so strong that the atomic system is driven into the nonlinear regime. The polarization P contains now two or more components

$$P(\nu) = aE(\nu) + bE^2(\nu)$$

The time behavior of the electric field can be described by a sinus function (E_0 is the amplitude) as

$$E(\nu) = E_0 \sin(2\pi\,\nu t).$$

Since the square of a sinus function has the doubled frequency

$$\sin^2(\nu t) = \tfrac{1}{2}\left[1 - \cos(2\nu t)\right]$$

it is obvious that the second component of the polarization P represents a field component with the doubled frequency. The prefactor b is called coefficient of nonlinearity; it depends on the crystal, on the wavelength and on the alignment of the crystal. Table 1.6 shows the coefficient of nonlinearity and other important parameters of various crystals. Beside the nonlinearity, self absorption and damage threshold are important for the use of crystals for SHG.

Table 1.6 Some optical properties of nonlinear crystals for frequency doubling of λ = 1.064 µm

Material	Effective nonlinearity (10^{-12} m/V)	Index of refraction n_0	Damage threshold (GW/cm^2)	Absorption (cm^{-1})
KD*P	0.37	1.49	0.5	0.005
KTP	3.18	1.74	0.5	0.010
LBO	1.16	1.56	2.5	0.005
BBO	1.94	1.65	1.5	0.005
$LiNdO_3$	4.7	2.23	0.10	0.002
$LiIO_3$	4.1	1.85	0.01	0.002

Figure 1.20 shows some ways for the technical realization of SHG. First a doubling crystal could be placed in a laser beam outside of the laser resonator as shown in Figure 1.20(a). This is the setup to investigate the optical properties of the crystal but not the optimum for SHG. As described at the beginning of this chapter, the light flux inside of the resonator is much higher than in the out coupled beam; therefore it is much smarter to place the nonlinear crystal inside of the resonator (Figure 1.20(b)). While the high reflection mirror is selected to reflect both ground wave with frequency ν as well as the frequency-doubled wave with 2ν, the output coupler is a dichroitic mirror with a high reflectivity for the ground wave at ν and a high transmission for the second harmonic with 2ν. The newest development is shown in Figure 1.20c, where laser crystal for optical amplification and the doubling crystal are combined into one crystal. The green laser pointers, widely used for presentations, are built-in this way.

There is another physical problem which should be mentioned: Usually the refraction index n for ground wave and for second harmonic are different, $n(\nu) \neq n(2\nu)$, which means both waves propagate with different speeds. A good scaling factor is the difference of the wave vectors $\Delta k = k(2\nu) - 2k(\nu)$. The intensity is maximized for a phase matching condition $\Delta k = 0$, which can be achieved under correct alignment in birefringent crystals. Under normal dispersion the second harmonic is slower and gets out of phase to the ground wave. Which means that second harmonic waves generated at $z = 0$ of the crystal and waves generated in the depth d may are out of phase. When a second harmonic wave generated in the depth d_c of the crystal has a phase mismatch of $\Delta\Phi = \pi$ to the wave generated at $d = 0$, all waves generated deeper in the crystal at $d > d_c$ will contribute to destructive interference. The output of $E(2\nu)$ oscillates as $\sin(\Delta k\ d/2)$. The coherence length of the crystal is defined as

$$d_c = \pi/\Delta k$$

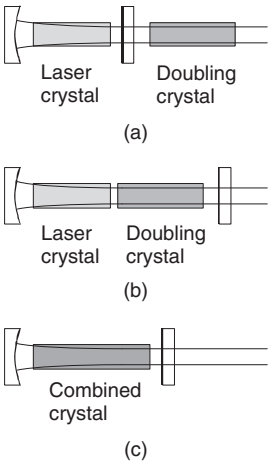

Fig. 1.20 Technical realization of SHG.

It is not economic to use a nonlinear crystal much longer than the coherence length d_c.

1.4 Quality of Laser Light Compared to Light of a Conventional Light Source

The difference of laser light compared to light of a conventional light source can be described by three major points:

1. *Coherence*. The strict phase correlation between all parts of the laser beam ensures a high ability for interference. The optical distance over which one part of a beam can be send on a detour and is further on able for inference with the other part of the beam is described by the optical coherence length. While light of light bulbs has a coherence length of only some micrometers, the coherence length of laser light can be several meters with commercial systems. All interferometric measurements regard on the coherence. Coherence is also visible in the photon statistics. While the statistics of photons of a conventional light source is given by a Bose–Einstein distribution, which means the photons come like in clusters, photons in coherent light follow a Poisson statistics, which means the time spacing between the photons is nearly constant. This photon statistics is very helpful for better signal-to-noise ratios in all measuring processes. The disadvantages of coherence are the so-called speckles; illumination does not appear homogeneously but as an area of brighter and darker spots.
2. *Monochromicity*. While the light emission of a light bulb is given by a hot metal filament which has a broad wavelength distribution from UV to IR, the emission of a laser is normally limited to $\Delta\lambda/\lambda = 10^{-6}$ (example He–Ne laser). Frequency stabilized systems can reach $\Delta\lambda/\lambda = 10^{-15}$. The narrow spectral width combined with a high-output power is used for selective excitation of atoms and molecules in high-resolution spectroscopy and for wavelength standards. As described in this chapter, some lasers are also designed to emit very broad spectra which are used for mode locking and frequency standards.
3. *High beam quality and high power*. Conventional light sources have bulky emission volume and usually emit in all directions. Concave mirrors and convex lenses are used to form a beam, but the total wave front is always a

superposition of many uncorrelated spherical wave fronts propagating in slightly different directions. A laser system, on the other hand, can emit an almost perfect Gaussian beam with a parallel wave front. Thus the beam can be focused onto a very small, only diffraction limited spot size. Since the divergence is very small, this beam can be guided over a long distance. The power densities which can be reached with laser systems are 10^{14} W/cm^2 and higher; the electric field of the laser beam is larger than the electric field of the atomic nucleus. High fields of this amplitude are used for plasma generation like in optical breakdown or for new X-ray sources. Pulsed laser systems can reach peak powers which are out of range for conventional light sources. Several systems can deliver Tera Watts, 10^{12} Watt; the outer dimensions are nicely described by the name Table Top Terawatt (T^3) lasers. Currently the most powerful laser system is Petawatt High Energy Laser for Heavy Ion Experiments (PHELIX) under construction at the GSI in Darmstadt, Germany.

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Further Reading

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