

Chapter 16

Some Other Lasers and Laser Amplifiers

We present further types of lasers: dye laser; chemical laser; X-ray laser; organic laser. And we discuss the principle of laser amplifiers. Another topic concerns optical damage.

16.1 Dye Laser

The dye laser was the first laser with a broad gain profile. The dye laser operates as a tunable cw laser or as picosecond laser (pulse duration ~ 1 ps). The tuning range of a dye laser is about 5% relative to the laser frequency. By the use of different dyes, the entire visible spectral range can be covered with laser radiation.

The dye laser is a vibronic laser (Fig. 16.1a). Transitions involve vibronic energy levels of the ground state (S_0) and of the first excited singlet state (S_1). The spatial extension of a molecule in the S_1 state is larger than in the S_0 state. Spontaneous emission of radiation determines the lifetime (2–5 ns). The vibronic levels are due to interaction of the electronic states with molecular vibrations. Optical pumping and fast nonradiative relaxation leads to population of the S_1 state. Laser radiation is generated by stimulated transitions from the lowest S_1 state of excited molecules to vibronic S_0 states. An optical transition is governed by the Franck–Condon principle.

In a dye laser (Fig. 16.1b), the solvent (water or an alcohol) that contains the dye molecules can continuously be pressed through a nozzle leading to a jet. The laser radiation passes the jet under the Brewster angle. The laser can be optically pumped with another laser (e.g., an argon ion laser) or with a lamp.

As an example of a dye molecule, we mention 7-hydroxycoumarin. The molecule has a benzene-like molecular structure (Fig. 16.1c). A corresponding laser contains coumarin solved in water (0.1 molar solution).

The $S_0 \rightarrow S_1$ absorption band of 7-hydroxycoumarin (Fig. 16.2) lies in the blue (450–470 nm) and the emission band in the green (580–600 nm). The fluorescence band (= fluorescence line) has a Gaussian-like shape. We attribute the line broadening to homogeneous broadening (Sect. 17.4). The linewidth of the

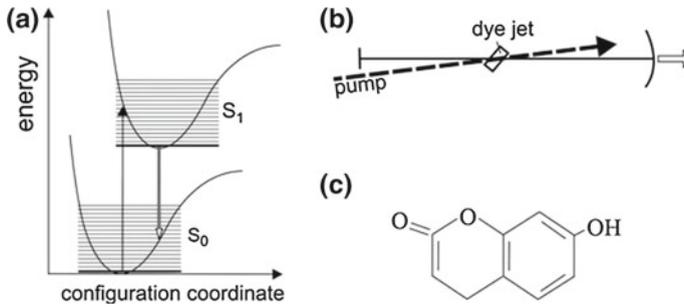


Fig. 16.1 Dye laser. **a** Principle. **b** Arrangement. **c** A dye molecule (7-hydroxycoumarin)

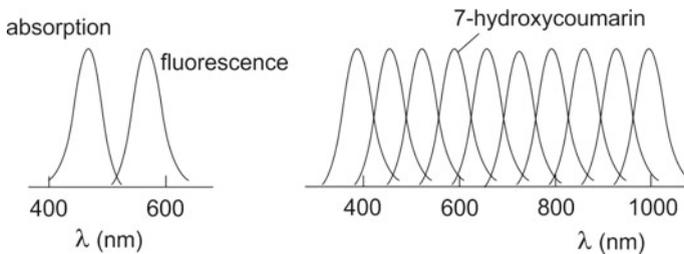


Fig. 16.2 Absorption and fluorescence of 7-hydroxycoumarin (left) and fluorescence bands of different dyes (right)

fluorescence line is about 20 THz. Dyes suitable as active media of dye lasers are available for the whole visible spectral range and also for the near UV and the near IR. The following list shows characteristic data.

- $\lambda_0 = 0.3\text{--}1.5 \mu\text{m}$ = wavelength of the line center of the gain curve; depending on the dye.
- $\tau_{\text{sp}} = 2\text{--}5 \text{ ns}$.
- $\Delta\nu_g = 10\text{--}20 \text{ THz}$.
- $\sigma_{21} = 5 \times 10^{-21}$ to $5 \times 10^{-19} \text{ m}^2$.
- Concentration $10^{-4}\text{--}10^{-3}$ molar ($N_0 = 0.1\text{--}1 \times 10^{25} \text{ m}^{-3}$).

Active media with dye molecules can have high gain coefficients (Problem 16.1).

Other applications of dyes. Dye molecules solved in water or in alcohol are saturable absorbers suitable for Q-switching of lasers (Sect. 12.6). Dye molecules find applications in medicine: dye molecules are suitable as markers in the photodynamic diagnosis and as active species in the photodynamic therapy of cancer [127–129].

16.2 Solid State and Thin-Film Dye Laser

The active medium of solid state dye laser can consist of a solid matrix, for instance polymethylmethacrylate, containing dye molecules. Suitable as pump sources are semiconductor lasers or diodes.

A thin-film dye laser consists of a thin film of dye molecules (embedded in a solid matrix) on a plane solid surface. A grating on the surface of the thin film can act as distributed feedback reflector (Sects. 25.4 and 34.4).

16.3 Chemical Laser

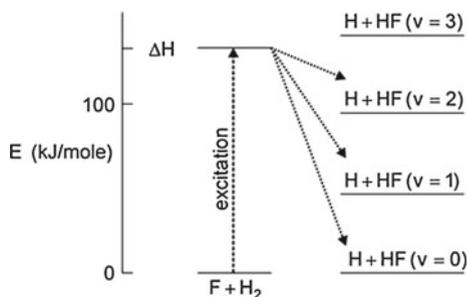
The basis of a chemical laser is a chemical reaction. In an HF laser, a gas discharge drives the reactions



The $(\text{HF})^*$ molecules are in excited vibrational-rotational states and emit radiation in the 3- μm range by transitions between vibrational-rotational states.

A chemical reaction changes the enthalpy H of a system. The two reactions described by (16.1) and (16.2) are exothermic reactions—producing reaction energy (= reaction heat ΔH). In the first reaction, (16.1), the reaction heat is $\Delta H = 1.3\text{ eV/molecule}$ (132 kJ/mole). A portion of the reaction heat is transferred to energy of excitation of vibrational-rotational states of the $v = 0, 1, 2$ vibrational levels (Fig. 16.3). The second reaction, (16.2), has a larger reaction heat ($\Delta H = 4.0\text{ eV/molecule}$) and results in excitation of vibrational-rotational energy levels up to the $v = 6$ vibrational level. The population of the different vibrational-rotational levels is a nonequilibrium population. Therefore, many laser transitions between different vibrational-rotational states can occur. The laser wavelengths are in the range between 2.7 and 3.3 μm .

Fig. 16.3 Chemical laser: principle of pumping



The HF laser operates as a continuous wave laser (driven by a gas discharge) or as TEA laser. The continuous wave laser can generate radiation of a power of 10 kW. The TEA laser pulses (of about 100 ns duration) have pulse energies of several kJ. The energy of a pulse corresponds to the energy of 100 J of laser radiation that can be generated per liter of the active material.

Other chemical lasers operating with other gases produce laser radiation in slightly different wavelength regions (DF, 3.5–4.5 μm ; HCl, 3.5–4.1 μm ; HBr, 4.0–4.7 μm).

16.4 X-Ray Laser

There are first steps toward a table-top X-ray laser. Figure 16.4a shows the principle of an X-ray laser [131–133]. Two strong visible laser pulses, focused onto a titanium plate, pump an X-ray laser in a two-step excitation.

- A laser pulse 1 (wavelength around 600 nm; pulse energy 20 J; duration 1 ns) produces a plasma with a large concentration of Ti^{12+} ions; the configuration of a Ti^{12+} ion corresponds to a [Ne] configuration ($2p^6$).
- A laser pulse 2 (frequency around 600 nm; 4 J; 1 ps) excites the plasma further. Then hot electrons in the plasma produce, by electron collisions, a population inversion, giving rise to stimulated emission of X-ray pulses.

In the second step, electrons collide with Ti^{12+} leading to excited Ti^{12+} ions in $2p^53s$ states (Fig. 16.4b). Transitions $3s \rightarrow 2p$ result in laser radiation at 18.2 nm (pulse energy 30 μJ , repetition rate 1 s^{-1}). The $2p$ states decays by fast radiative transitions.

X-ray lasers with other solids (Ge, Pd, Ag, etc.) generate radiation pulses at other wavelengths (6–40 nm) in the soft X-ray region.

The X-ray laser presented here is a mirrorless laser, there is no feedback with a resonator. Laser radiation is generated by amplified spontaneous emission (ASE). During propagating through the plasma, spontaneously generated radiation is amplified by stimulated emission of radiation.

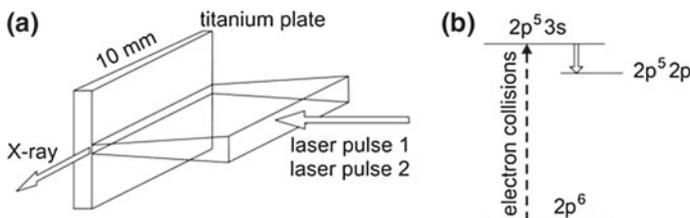


Fig. 16.4 X-ray laser. **a** Arrangement. **b** Laser transition in Ti^{12+}

16.5 Random Laser

A random laser can consist of an optical powder, for example a powder of Nd^{3+} :YAG crystallites. Due to light scattering at the powder particles, the light emitted spontaneously is amplified by stimulated emission; for information about solid state random lasers, see [134].

16.6 Optically Pumped Organic Lasers

We will treat optically pumped organic lasers in a later chapter (Sect. 34.4); then we will have available concepts, described in Chap. 18 and in chapters on semiconductor lasers, that are useful to explain how gain of radiation in an organic medium can occur.

16.7 Laser Tandem

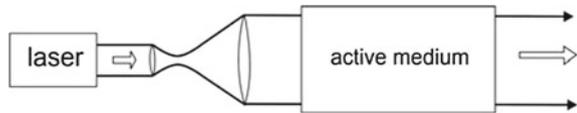
A laser tandem is suitable for generation of laser radiation of high beam quality. A semiconductor laser, with a high efficiency of conversion of electric power to laser radiation, pumps a solid state laser. The frequency doubled radiation of this laser pumps a third laser. A semiconductor laser has a low beam quality. The combination of both type of lasers is most favorable: the use of a semiconductor laser as pump laser of a solid state laser allows for an efficient conversion of electric energy to high quality laser radiation.

Example A semiconductor laser pumps a Nd:YAG laser, then the radiation is frequency-doubled. The frequency doubled radiation finally pumps a titanium–sapphire laser.

16.8 High-Power Laser Amplifier

In a high-power laser system (Fig. 16.5) consisting of a laser and a laser amplifier, the laser beam is expanded by the use of a telescope in order to avoid optical damage of the active medium of the amplifier. The (single-pass) gain factor G_1 of a laser amplifier can have a value of the order of 10. By the use of laser amplifiers in series, very large power levels can be obtained. Table 16.1 shows data of three high-power laser systems (t_p = pulse duration; W_p = pulse energy; P = pulse power; ν_{rep} = repetition rate).

- *Femtosecond titanium–sapphire laser amplifier.* The radiation of a femtosecond titanium–sapphire laser can be amplified with a laser amplifier containing optically

Fig. 16.5 Laser amplifier**Table 16.1** High-power laser systems

Laser	λ	t_p	W_p	$P(W)$	ν_{rep}
Ti:S	780 nm	100 fs	1 mJ	10 GW	1 kHz
Nd:glass	1.06 μm	1 ns	10 kJ	10 TW	1 h
TEA CO ₂	10.6 μm	100 ns	1 J	10 MW	10 Hz

pumped titanium–sapphire as the active material. An optical switch can reduce the pulse repetition rate (which is of the order of 100 MHz) of the radiation of a femtosecond titanium-sapphire laser to a value of, for example, 1 kHz.

- *Neodymium glass laser amplifier.* By amplification of a light pulse of a neodymium-doped glass laser with glass laser amplifiers, a pulse of extremely high pulse energy can be generated. The beam emitted by a glass laser is widened and amplified by a first amplifier, then widened and amplified by a second amplifier and so on. (It is possible to produce glass in cylinders of large diameter.) A radiation pulse generated by a laser amplifier system (or pulses generated by systems in parallel), focused on a target containing deuterium and tritium can heat up the target to a temperature at which nuclear fusion processes can occur (laser fusion); a laser pulse can produce a plasma of a temperature of the order of 100 million degrees.

16.9 Fiber Amplifier

Fiber amplifiers consisting of glass doped with rare earth ions are suitable for amplification of radiation in the 1–3 μm range; fiber amplifiers make use of the same rare earth-doped glasses as fiber lasers (Sect. 15.7 and Chap. 18). By the use of amplifiers, radiation at kW power levels can be generated.

The erbium-doped fiber amplifier—that is of great importance for long-distance optical communications—will be treated in Chap. 18.

16.10 Optical Damage

A strong radiation field in a transparent solid material can lead to optical damage. Different materials have different damage thresholds. The damage threshold of a material depends strongly on the wavelength of the radiation. The damage threshold is orders of magnitude larger for pulses of 10 fs duration than for pulses of 1 ns

duration. Accordingly, the optical-damage threshold can have values between 10kW per cm (or smaller) and 20MW per cm.

Optical damage can be caused by interband transitions of electrons and subsequent impact ionization processes [135, 136]. An interband transition in a crystal in a strong electromagnetic field can be due to a multiphoton transition. Interband transitions excite electrons into the conduction band. Subsequently, the electrons in the conduction band gain energy by absorption processes, i.e., due to acceleration of the conduction electrons by the optical field. Highly excited conduction electrons excite, by impact ionization, further electrons from the valence band to the conduction band. The impact ionization is an avalanche process that can lead to optical breakdown associated with crystal damage.

16.11 Gain Units

The power of a light beam that traverses an amplifier increases from P_0 to P . We can characterize the increase in different ways, assuming that the gain does not change along the path of the beam:

- $G = P/P_0 = \text{gain factor}$.
- $G = e^{\alpha L}$, where α is the gain coefficient (in m^{-1}) and L (in m) the length of the gain medium.
- $1 \text{ dB} (= 1 \text{ dB}) = 10 \times \log(P/P_0) = 10 \times 0.43 \times \alpha L = 4.3 \times \alpha L$.
- $(1 \text{ B} = 1 \text{ Bel} = 10 \text{ dB})$.
- $1 \text{ dB/m} = L^{-1} \times 10 \times \log(P/P_0) = 4.3\alpha$.
- $1 \text{ dB m} = 1 \text{ dB mW} = 1 \text{ dB} \times 1 \text{ mW} = \text{a unit of gain of an amplifier}$.

Example erbium fiber amplifier; $\alpha = 0.5 \text{ m}^{-1}$ and $L = 14 \text{ m}$; gain = 2.15dB/m; $G = 10^3$.

References [127–136].

Problems

16.1 Dye laser (length of the active medium 1 mm; beam diameter 0.2mm; reflectivity of the output coupling mirror $R = 0.7$; frequency 500 THz).

- (a) Determine the threshold condition.
- (b) Determine the output power at pumping 10 times above threshold.

16.2 Laser amplifier. To amplify femtosecond pulses emitted by a titanium-sapphire laser, an optical switch reduces the pulse repetition rate to 1 kHz. By passing through two amplifier stages (optically pumped titanium-sapphire crystals), each with a single path gain of 10, intense laser pulses are generated. Determine (by use of the data of Problem 13.2) the pulse power and the average power after amplification.

16.3 Momentum of a photon and radiation pressure.

- (a) When an atom at rest emits a photon, then the atom experiences a recoil. Estimate the velocity of a neon atom that was originally at rest and emitted a photon (wavelength 632 nm).
- (b) Estimate the average velocity of a spherical target (diameter 0.2 mm) consisting of frozen deuterium that absorbed an intense light pulse (energy 100 J, wavelength 1.05 μm).

16.4 Radiation of a titanium sapphire laser amplifier system (pulse power 1 GW, wavelength 780 nm, pulse duration 100 fs) is focused to an area of diameter 10 μm^2 . Determine the intensity, the photon density, the energy density, the amplitude of the electric field in the focus.

16.5 Magnetic field of a light wave.

Determine for the example of the preceding problem the amplitude of the magnetic field of the electromagnetic wave in the focus. Compare the amplitude with Earth's magnetic field. The amplitude of the magnetic field of a plane wave is $B_0 = (1/c)A$, where A is the amplitude of the electric field. The magnitude of Earth's magnetic field on the surface ranges from 25 to 65 μT .

16.6 Material processing.

The radiation of a high power laser with amplifier (pulse duration 1 ps, pulse power 1 MW, diameter 0.02 mm) is used to drill a hole in a metal foil (thickness 0.2 mm). How many shots are necessary?