Chapter 12
Different Ways of Operating a Laser

In this chapter, we describe techniques used to operate lasers as continuous wave lasers or as pulsed lasers—in the next chapter we will treat femtosecond lasers.

We discuss single mode lasers. We mention spectral hole burning, occurring in lasers that operate with inhomogeneously broadened transitions. We give a short introduction to various methods of Q-switching of lasers used to generate laser pulses.

Furthermore, we describe two applications of continuous wave lasers—optical tweezers and gravitational wave detector.

12.1 Possibilities of Operating a Laser

Lasers can operate as continuous wave lasers, as pulsed lasers, or as femtosecond lasers. Lasers operated in different ways at different wavelengths have various applications in physics, chemistry [77, 78], biology, and medicine [79–82, 127–129, 332]. An early application was the holography [83, 84].

There are continuous wave lasers and different types of pulsed lasers:

- The *cw (continuous wave) laser*. Continuous pumping maintains the laser oscillation.
- *Pulsed laser*. A pump pulse generates a population inversion. Or more general: each laser that delivers pulses is a pulsed laser.
- *Q-switched laser*. In the Q-switched laser, the quality factor Q of the laser resonator varies with time. The Q factor is small for most of the time and large for a short time. During the time of small Q, population in the upper laser level is collected. During the time of large Q, laser oscillation occurs and the population of the upper laser level is strongly reduced.

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- *Giant pulse laser*. This is a Q-switched laser with an upper laser level that has a very long lifetime (for instance 1ms); pumping leads to a large concentration of atoms in the upper laser level.
- *Femtosecond laser* (Chap. 13). The pumping is continuous. For most of the time, the Q factor of the resonator is small but it is large during short time intervals that follow each other periodically. The laser emits a coherent pulse train.

12.2 Operation of a Laser on Longitudinal Modes

A *mode diaphragm* eliminates transverse modes. The transverse modes suffer stronger diffraction than longitudinal modes and cannot reach the threshold condition. This mode selection makes it possible to operate a laser on longitudinal modes, 00l, $00(1+1)$, ...

There are different possibilities of the operation of a laser on longitudinal modes:

- *Single line laser*, operated on a few neighboring longitudinal modes at frequencies in a narrow frequency range.
- *Single mode laser*, operated on a single longitudinal mode.
- *Mode-locked laser*, operated on a large number of longitudinal modes with frequencies in a large frequency range—the phases of the electromagnetic fields of different longitudinal modes are coupled (locked) to each other (Chap. 13).

12.3 Single Mode Laser

Many lasers (e.g., the helium–neon laser) have narrow gain profiles, but oscillate on a few modes (Fig. 12.1). By inserting an *etalon* (a plane parallel plate) into the resonator, selection of a single mode is possible. An etalon represents a low-Q resonator of the resonance wavelength

$$\lambda_s = \frac{2nd}{s} \cos\theta, \tag{12.1}$$

where n is the refractive index, d the thickness of the etalon, and θ the angle between the laser beam within the etalon and the normal to the etalon; s (an integer) is the order of resonance. Rotation of the etalon changes the angle θ and the resonance wavelength λ_s.

Example Without an etalon in the resonator, a helium–neon laser oscillates on about three modes at once (Fig. 12.1, lower part) but with an etalon on a single mode.

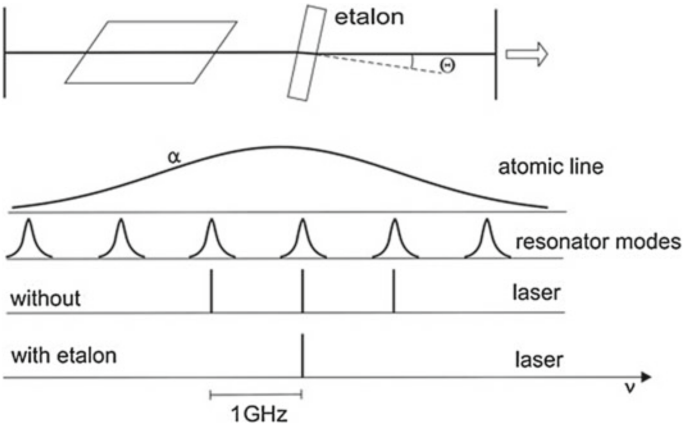

Fig. 12.1 Mode selection with an etalon; arrangement and result for a helium–neon laser ($\lambda = 633\,\text{nm}$, $\nu = 474\,\text{THz}$)

12.4 Tunable Laser

A laser with a broadband gain profile oscillates on a single line if the laser resonator contains an appropriate wavelength selective element. We mention three wavelength selective elements suited to force a laser with a broad gain profile to emit a single line.

- *Prism* (Fig. 12.2a). A prism in the resonator selects the laser wavelength. The laser is tunable; rotation of the prism changes the wavelength. With an etalon additionally inserted into the resonator, a laser is able to oscillate on a single mode.
- *Echelette grating* (Fig. 12.2b). An echelette grating acts as one of the two reflectors of a laser resonator. In the *Littrow arrangement*, radiation that is incident on the echelette grating is diffracted in first order. The diffracted beam has the reverse direction relative to the incident beam. A rotation of the grating changes the wavelength of the backward diffracted radiation and thus the laser wavelength. A mirror telescope extends the diameter of the beam in order to obtain a higher resolving power and, furthermore, to reduce the field strength at the surface of the echelette grating thus avoiding damage of the grating. With an etalon that is additionally inserted into the resonator, a laser is able to oscillate on a single mode.
- *Birefringent filter* (Fig. 12.2c). The frequency selective element is a birefringent plate (e.g., a crystal of KDP = potassium dihydrogen phosphate) located between two polarizers in the laser resonator. The optic axis of the birefringent plate is oriented along the surface of the plate. The birefringent plate splits a beam of polarized radiation, incident under the Brewster angle, into an ordinary and an extraordinary beam. Behind the plate, the radiation has elliptical polarization and

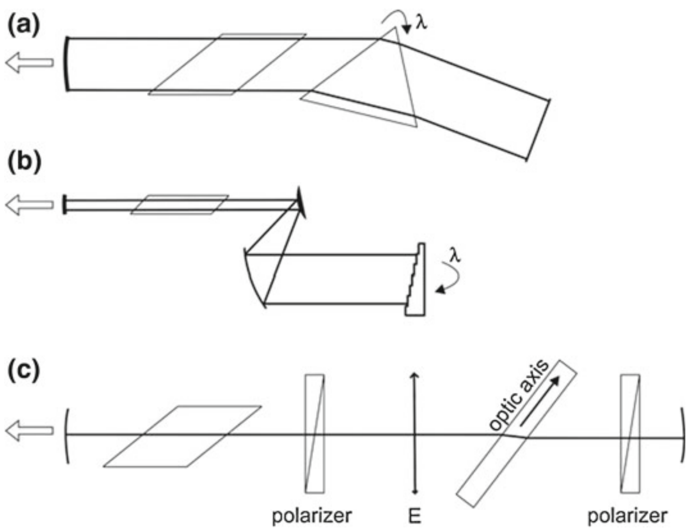

Fig. 12.2 Tunable laser. **a** Line selection with a prism. **b** Line selection with a grating. **c** Line selection with a birefringent filter

the second polarizer causes loss. There is no loss if the change of the phase between the ordinary and extraordinary beam is a multiple of π,

$$\frac{2\pi}{\lambda}(n_e - n_o)l_p = s \times \pi, \tag{12.2}$$

where n_e is the refractive index of the extraordinary beam, n_o the refractive index of the ordinary beam, l_p the length of the plate along the beam direction, and s is an integer. By rotating the plate while keeping the angle of incidence at the Brewster angle, the direction of the optic axis relative to the direction of the electric field vector (E) changes, leading to changes of n_e and of λ.

12.5 Spectral Hole Burning in Lasers Using Inhomogeneously Broadened Transitions

The oscillation behavior of a continuous wave laser depends on the type of line broadening.

A cw laser based on a homogeneously broadened line oscillates at the frequency of maximum gain (Fig. 12.3). When the population inversion begins, laser oscillation at the line center—where the gain coefficient α has its maximum—builds up. The onset of laser oscillation leads to a reduction of the population difference, from $(N_2 - N_1)_0$ to $(N_2 - N_1)_{th}$ for frequencies at the line center. Accordingly, the gain coefficient

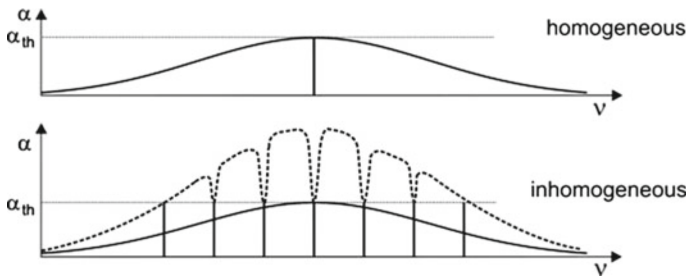

Fig. 12.3 Continuous wave laser based on a homogeneously broadened transition (*upper part*) or an inhomogeneously broadened transition (*lower part*)

changes from the small-signal gain coefficient to the threshold gain coefficient α_{th} for frequencies at the line center. Then the population difference and the gain coefficient are not sufficient for laser oscillation at frequencies in the wings of the line.
Examples of continuous wave lasers based on transitions with homogeneous line broadening: Nd:YAG laser; titanium–sapphire laser.

If laser oscillation is based on an inhomogeneously broadened line, a cw laser can oscillate on all modes that reach the threshold gain. Laser oscillation on one mode does not directly influence the population of two-level atomic systems that contribute to oscillation on other modes.
Examples of lasers based on transitions with inhomogeneous broadening: helium–neon laser; cw CO_2 laser.

The gain curve $\alpha(\nu)$ of a laser operated with an inhomogeneous broadened line shows 'holes" (*see* Fig. 12.3)—the effect is a manifestation of *spectral hole burning*. Irradiation of a medium with laser radiation can lead to a hole in the absorption spectrum of a medium. (Generation of a spectral hole in a medium by using a pulsed laser and the probing of the spectrum with cw radiation or with probe pulses allows for the measurement of the lifetime of a spectral hole; different methods of spectral hole burning are widely used in physics and chemistry for studying spectral properties of various media.)

12.6 Q-Switched Lasers

We discuss a few methods of Q-switching.

- *Mechanical Q-switching* (Fig. 12.4a). The reflector of the laser resonator rotates (for example with an angular frequency of 100 turns per second). The resonator has a high Q factor only during a short time in which the rotating mirror is oriented parallel to the output coupling mirror. During the time of a low Q factor, the upper laser level is populated and during the time of large Q, it is depopulated.

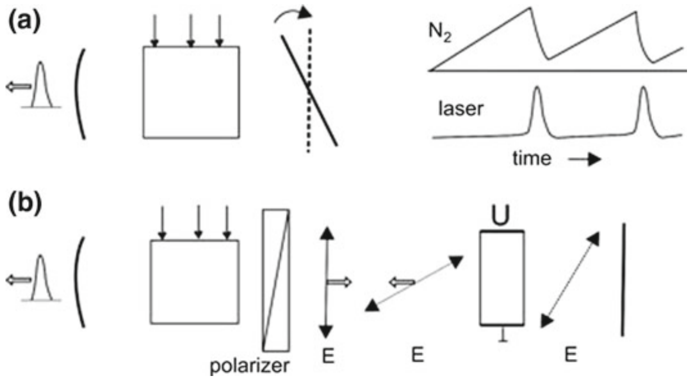

Fig. 12.4 Q-switching. **a** Mechanical and **b** electro-optic Q-switching

Example Generation of pulses (duration 100 ns) with a Q-switched CO_2 laser.

- *Electro-optic Q-switch making use of the Pockels effect* (Fig. 12.4b). A Pockels cell switches the Q factor of the laser resonator from a low to a high value. An optically isotropic crystal becomes birefringent when a static voltage (U) across the crystal is applied and produces a static field E_s in the crystal. Then the refractive indices for a light field E are different for the polarization directions parallel and perpendicular to the static field. The difference of the refractive indices is given by

$$n(\boldsymbol{E}||\boldsymbol{E}_s) - n(\boldsymbol{E}\perp\boldsymbol{E}_s) = aU, \tag{12.3}$$

where a is a material constant. A Pockels cell with applied voltage rotates the polarization direction of the light after two transits through the cell by $\pi/2$. A polarizer blocks the radiation. When the voltage is quickly turned off, the crystal is no longer blocking the radiation—a laser pulse builds up in the resonator. The Pockels effect is large for KDP (for a specific crystal orientation). A voltage of about 25kV is necessary for Q-switching with a crystal of 5mm height and 5 cm length.

- *Electro-optic Q-switch making use of the Kerr effect*. In a Kerr cell, an isotropic medium becomes birefringent under the action of a static field. The difference between the refractive indices of the ordinary and the extraordinary beam varies quadratically with the voltage,

$$n(\boldsymbol{E}||\boldsymbol{E}_s) - n(\boldsymbol{E}\perp\boldsymbol{E}_s) = b\,U^2. \tag{12.4}$$

A static field orients the molecules in a Kerr cell giving rise to birefringence. The effect is especially large for liquid nitrobenzene ($C_6H_5NO_2$). A voltage of about 10 kV is necessary at a cell size of 1 cm height and 1 cm length.

- *Q-switching with a saturable absorber* (Fig. 12.5a). As an example of Q-switching with a saturable absorber, we discuss Q-switching with a dye solved in a liquid. The

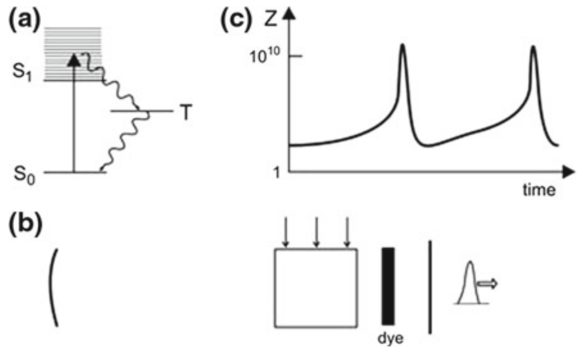

Fig. 12.5 Q-switching with a saturable absorber. **a** Saturation process for dye molecules. **b** Arrangement. **c** Number of photons in the laser resonator

ground state of a dye molecule is a singlet state (S_0). The two lowest excited states are a singlet state (S_1) and a triplet state (T), at a smaller energy. By transitions $S_0 \rightarrow S_1$, laser radiation is absorbed and by nonradiative transitions $S_1 \rightarrow$ T, molecules are transferred into the triplet state. A triplet state has a long lifetime (0.1–1 μ s); the decay of a triplet state occurs mainly via nonradiative transitions. A Q-switched laser based on a saturable absorber (Fig. 12.5b) is continuously pumped. At the start of the pumping, a laser field begins to build up. The buildup of a laser field occurs slowly because of absorption of radiation by the dye molecules. The absorption saturates the dye molecules, then almost all dye molecules are in the triplet state and the dye cell becomes transparent giving rise to generation of a strong laser pulse (Fig. 12.5c). During the buildup of a pulse, the population of the upper laser level becomes reduced to a low value. Due to relaxation of the dye molecules to their ground state, absorption sets in and the Q value becomes small. The buildup of a laser field begins again. Pumping is possible with radiation of another laser.

We will later (in Sect. 13.2) discuss other methods of Q-switching. Dye molecules are discussed in more detail in Sect. 16.1.

12.7 Longitudinal and Transverse Pumping

An active medium can be obtained by longitudinal or transverse pumping.

- *Examples of longitudinal pumping*: pumping with a gas discharge, with the electric field being parallel to the laser beam (Chap. 14); optical pumping with laser radiation whose propagation direction is along the laser beam (Sect. 5.2).
- *Examples of transverse pumping*: pumping with a gas discharge, with the electric field, which drives the discharge, oriented perpendicular to the laser beam (Sect. 14.8); optical pumping with a gas discharge lamp.

12.8 An Application of CW Lasers: The Optical Tweezers

The optical tweezers are suitable for optical trapping of single biomolecules solved or suspended in a liquid. The optical tweezers have many applications especially in biology and chemistry.

- *Biology*. Spectroscopy of trapped single molecules (e.g., red blood cells); study of properties of DNA; sorting of cells.
- *Chemistry*. Spectroscopy of trapped single organic macromolecules.

Figure 12.6a illustrates the principle of the optical tweezers. A glass pearl (diameter 1–10 μm), which is transparent for light, is trapped in the focus of a laser beam. The beam (power $\sim$ 1 mW) is strongly focused. When the glass pearl has a position below the focus, the pearl acts as a lens and the light leaves the pearl at an angle of aperture that is smaller than the angle under which it enters the pearl. Accordingly, the light gains momentum in the direction of the light beam, namely downward, and therefore the pearl gains momentum toward the focus.When the pearl has a position above the focus, it acts as a diverging lens and the force on the pearl is downward. The light leaves the pearl under the same angular distribution as it enters the pearl and there is no momentum transfer. When the glass pearl is located at the height of the focus but shifted to the left, the light beam is deflected to the left and the pearl moves toward the focus. Finally, when the pearl is on the right side of the focus, there is a force toward the left. Thus, the stable location of the pearl is the focus of the lens.

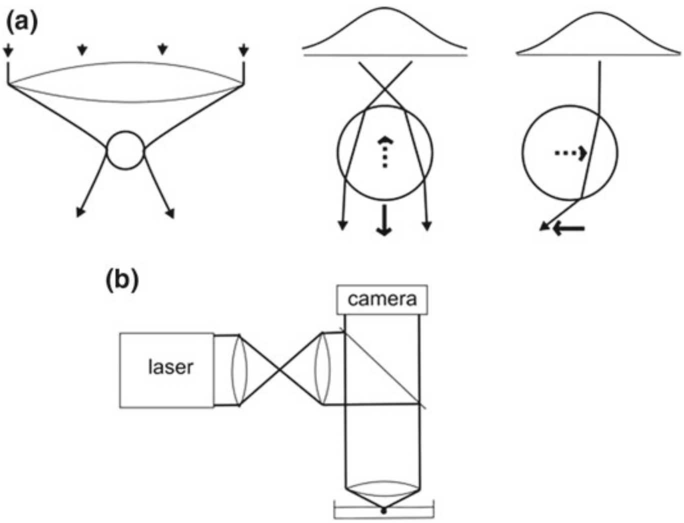

Fig. 12.6 Optical tweezers. **a** Trapping of a glass pearl in a focused laser beam. **b** Arrangement

An optical tweezers system can be realized as a modified microscope (Fig. 12.6b). The object lens produces a strongly focused beam of laser radiation. A camera monitors reflected radiation. The optical tweezers are able to trap a macromolecule in a solvent. Investigation of a trapped molecule is possible by using spectroscopic techniques, e.g., by studying fluorescence radiation. Applications in biology are described in [79].

12.9 Another Application: Gravitational Wave Detector

An extraordinary ambitious project concerns the goal to detect gravitational waves (*see*, for instance, [85]). The collapse of a big star generates (according to the general theory of gravitation) a gravitational wave, propagating with the speed of light. The wavelength of a gravitational wave is of the order of the extension of the collapsing star. A gravitational wave is expected to compress the space in a direction perpendicular to the propagation direction and to dilate the space in the other direction perpendicular to the propagation direction. At present, gravitational wave detectors based on the Michelson interferometer are built and tested at many places.

The center of the gravitational wave detector (Fig. 12.7) is a Michelson interferometer with a laser light source. The Michelson interferometer has two arms arranged perpendicular to each other. A beam splitter divides the laser beam into two beams. A gravitational wave pulse traversing the Michelson interferometer is expected to shorten one arm and to lengthen the other arm. Estimates of the effect suggest that the path length difference may only be of the order of 10^{-22} m for $L_1 = L_2 = 1$ km. The experiment requires an extremely high stability of the laser and of the arrangement and, furthermore, an extremely high sensitivity of detection. To have a chance to observe a signal, the arms have to be very long (of the order of 1 km or much longer). Making use of satellites, very large arms are realizable. The arms have slightly different lengths ($L_1 - L_2 = \lambda/4$, where λ is the wavelength of the laser radiation) in order to have a high sensitivity of detection.

In 2016, observation of a gravitational wave has been reported [311].

References [1–4, 6, 77–85, 127–129, 310, 311].

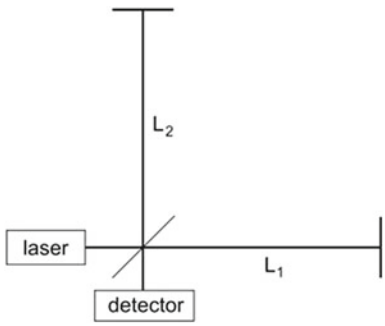

Fig. 12.7 Gravitational wave detector

Problems

12.1 Resonance condition for a planparallel plate. Derive the resonance condition (12.1) for a planparallel plate. [*Hint*: Determine the difference of the optical path of a beam directly reflected at the surface of the plate and a beam reflected at the backside of the plate.]

12.2 Michelson interferometer. A Michelson interferometer operates with a parallel laser beam (wavelength $\lambda = 580$ nm; P_0 = power of the laser radiation).

(a) Calculate the intensity $I(x)$ at the detector for a length difference x when one arm has the length L and the other arm the length $L + x$.
(b) Determine the path difference δx for values of x in the interval $x_0 \leq x \leq x_0 + \lambda$ for $x_0 = 1$ km that leads to the largest signal-to-noise ratio for the signal.
(c) Estimate the change of the signal if one of the arms changes its length by $\delta L/L = 10^{-15}$ and the other arm by $\delta L/L = -10^{-15}$. [*Hint*: The beam splitter in the Michelson interferometer splits an incident electromagnetic field into two fields.]

12.3 It is possible to reduce suddenly the reflectivity of the output mirror of a laser. Show, qualitatively, that this "cavity dumping" results in a much stronger laser pulse than without cavity dumping.