Chapter 1
Introduction

We will ask and partly answer a few questions. What is the difference between a laser and a light bulb? In which frequency ranges are lasers available? Which are the sizes and the costs of lasers? Why is it necessary to have different types of lasers in the same frequency range? We will also mention some specific lasers and we will discuss the concept of the book.

1.1 Laser and Light Bulb

The *spatial and temporal* coherence makes the difference between a laser and a light bulb (Fig. 1.1). While a lamp emits uncorrelated wave trains into all spatial directions, a laser generates coherent waves and the waves can have a high directionality. Which are the possibilities of generation of spatially and temporally coherent waves? A laser can generate a coherent continuous wave or a coherent pulse train. Extreme cases of generation of visible radiation are as follows:

- The *continuous wave laser* (cw laser) emits a continuous electromagnetic wave. The field is spatially and temporally coherent.
- The *femtosecond laser* emits an electromagnetic wave consisting of a pulse train; the duration of a single pulse of a train can be as short as 5 fs (1 fs = 1 femtosecond $= 10^{-15}$ s). The field of a pulse train is spatially and temporally coherent too.

Beside continuous wave lasers and femtosecond lasers, there are pulsed lasers producing laser pulses with durations in the picosecond, nanosecond, microsecond, or millisecond ranges. We use the abbreviations:

- 1 ms = 1 millisecond $= 10^{-3}$ s
- 1 μs = 1 microsecond $= 10^{-6}$ s
- 1 ns = 1 nanosecond $= 10^{-9}$ s
- 1 ps = 1 picosecond $= 10^{-12}$ s

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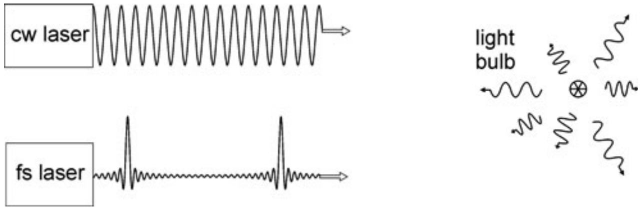

Fig. 1.1 Continuous wave (*cw*) laser, femtosecond (*fs*) laser and light bulb

- 1 fs = 1 femtosecond = 10^{-15} s
- 1 as = 1 attosecond = 10^{-18} s

The acronym LASER means: *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation. It developed to *laser* = device for generation of coherent electromagnetic waves by stimulated emission of radiation. The *maser* (=*microwave laser*) makes use of microwave amplification by stimulated emission of radiation.

1.2 Spectral Ranges of Lasers and List of a Few Lasers

Figure 1.2 shows wavelengths and frequencies of spectral ranges of the electromagnetic spectrum — from X-rays over the ultraviolet (UV), the visible, the near infrared (NIR), the far infrared (FIR) spectral ranges to microwaves and radiowaves. The frequency ν of an electromagnetic wave in vacuum obeys the relation

$$\nu = c/\lambda, \tag{1.1}$$

where c (= $3 \times 10^8\,\mathrm{m\,s^{-1}}$) is the speed of light and λ the wavelength. Abbreviations of frequencies are as follows:

- 1 MHz = 1 megahertz = 10^6 Hz
- 1 GHz = 1 gigahertz = 10^9 Hz
- 1 THz = 1 terahertz = 10^{12} Hz
- 1 PHz = 1 petahertz = 10^{15} Hz

The visible spectral range corresponds to a frequency range of about 430–750 THz (wavelength range about 400–700 nm). Optics and light refer to electromagnetic waves with vacuum wavelengths smaller than about 1 mm, i.e., with frequencies above 300 GHz. Lasers are available in the ultraviolet, visible, near infrared, far infrared, and microwave regions. Lasers of the range of X-rays are being developed. The spectral ranges in which lasers are available extend from the GHz range over the THz range to the region above 1,000 THz.

The ancient Greeks understood $\mu\epsilon\gamma\alpha$ (mega) as something that was exceeding all measurable things, $\gamma\iota\gamma\alpha$ (giga) had to do with the giants, $\tau\epsilon\rho a$ (tera) included their

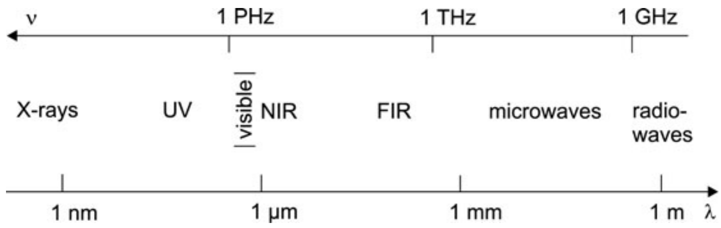

Fig. 1.2 Spectral ranges of lasers

Table 1.1 Laser wavelengths, frequencies, and quantum energies

Laser	λ	ν (THz)	$h\nu$ (10^{-19} J)	P_{out}
HeNe	633 nm	474	3.1	1 to 10 mW
CO_2	10.6 μm	28	0.18	1 W to 1 kW
Nd:YAG	1.06 μm	283	1.9	2 W
TiS	830 nm	360	2.4	100 mW to 5 W
Fiber	1.5 μm	200	1.3	1 W
Semiconductor	840 nm	357	2.4	10 to 100 mW
QCL	5 μm	600	0.25	10 to 100 mW

gods, and πετα (peta) was the largest one could imagine — world, giants, gods, and all spheres together. The notation "terahertz" was introduced shortly after the discovery of the helium–neon laser, which emits coherent radiation at a frequency near 474 THz (wavelength 633 nm).

Table 1.1 shows data of a few continuous wave lasers. The data concern: λ = laser wavelength; ν = laser frequency; $h\nu$ = quantum energy of the photons of a laser field (= photon energy); $h = 6.6 \times 10^{-34}$ J s; P_{out} = output power.

- *Helium–neon laser* (HeNe laser). It generates red laser light of a power in the milliwatt range. Helium–neon lasers emitting radiation at other wavelengths are also available.
- *CO_2 laser* (carbon dioxide laser). It produces infrared radiation of high power at wavelengths around 9.6 and 10.6 μm.
- *Neodymium YAG laser* (Nd:YAG laser; YAG = yttrium aluminum garnet). The laser is a source of near infrared radiation (wavelength 1.06 μm).
- *Titanium–sapphire laser* (TiS laser). The laser operates as a continuous wave laser or as a femtosecond laser. The cw titanium–sapphire laser is tunable over a very wide spectral range (650–1080 nm).
- *Fiber laser*. Fiber lasers (= lasers with glass fibers, doped with rare earth ions) operate in the wavelength range of about 0.7–3 μm.
- *Semiconductor laser*. Semiconductor lasers (more accurately: bipolar semiconductor lasers) are available in the entire visible, the near UV, and the near infrared. The wavelength and the power (from the nW range to the 100 mW range) of radiation generated by a semiconductor laser depend on its design. A stack of semiconductor lasers can produce radiation with a power up to the kW range.

Table 1.2 Pulsed lasers

Laser	λ	t_p	W_p	Pulse power	ν_{rep}	P_{av}
Excimer	351 nm	50 ns	1 J	20 MW	10 Hz	10 W
Nd:YAG	1.06 μm	6 ns	100 mJ	16 MW	100 Hz	10 W
TiS	780 nm	10 fs	10 nJ	1 MW	50 MHz	0.5 W

- *Quantum cascade laser* (QCL). A QCL is a type of semiconductor laser that produces radiation in the infrared or in the far infrared. The laser wavelength of a quantum cascade laser depends on its design.

Table 1.2 shows data of a few pulsed lasers: t_p = pulse duration = halfwidth of a pulse on the time scale = FWHM = full width at half maximum; W_p = energy of radiation in a pulse = pulse energy; pulse power = W_p/t_p; ν_{rep} = repetition rate; P_{av} = average power.

- *Excimer laser*. It is able to produce UV radiation pulses of high pulse power; the wavelength given in the table is that of a laser operated with XeF excimers. Excimers with other materials generate radiation at other wavelengths (XeCl, $\lambda = 308$ nm; KrF, 248 nm; ArF, 193 nm).
- *Neodymium YAG laser*. Depending on the design of a pulsed neodymium YAG laser, the pulse duration can have a value between 5 ps or a value that is larger than that given in the table. The average power can be larger than 10 W.
- *Titanium–sapphire femtosecond laser*. The power is large during a very short time.

A laser system, consisting of a laser oscillator and a laser amplifier, can generate radiation pulses of much larger pulse power levels (Sect. 16.8).

1.3 Laser Safety

Laser safety has to be taken very seriously: a laser emitting visible radiation of 1 mW power leads to a power density in the focus (area λ^2) of a lens — for instance, in the focus of the lens of an eye — of the order of 10^9 W m^{-2} (10^5 W cm^{-2}). Such a power density can lead to damage of an eye. Dear reader, please take care of the corresponding safety rules when you experiment with a laser!

1.4 Sizes of Lasers, Cost of Lasers, and Laser Market

There are lasers of very different size.

- A gas laser or a solid state laser has a typical length of 1 m (down to 10 cm). The price of a laser is between 100 U.S. dollar and 1 million dollar.

- A free-electron laser has a typical length of 10 m (not taking account of a much larger accelerator). The price of a free-electron laser lies, depending on its properties, between 10 million and several billion dollar.
- The smallest lasers are semiconductor lasers with sizes ranging from about 1 mm to smaller sizes. Microlasers with dimensions of the order of 10 μm can be fabricated; nanolasers — with extensions below 1 μm — may be suitable for special applications. Mass production (at a price of 10 dollar per laser or much less) resulted in a great variety of applications of semiconductor lasers.

The *laser market* (Fig. 1.3a) is strongly growing. The development may be similar as for the computer market. After the discovery of the transistor in 1946, it took about 50 years until the transistor became widely distributed — as the essential basis of a computer. The main breakthrough was due to miniaturization realized in the microelectronics, and due to integration of transistors in large systems. The laser, with its first operation 14 years after the transistor, is beginning to be widely spread as a part of devices of the daily life. The integration of the lasers in other devices and in large systems became possible by the development of the semiconductor lasers and their miniaturization.

The laser market offers a large variety of different lasers designed for particular applications. The laser field is in a rapid development; improvements of laser designs, new types of lasers, and new applications make the field strongly growing. We mention here the *industrial lasers*, machines suitable for various applications. In 2009, the main contributions to the turnover in the market of industrial lasers

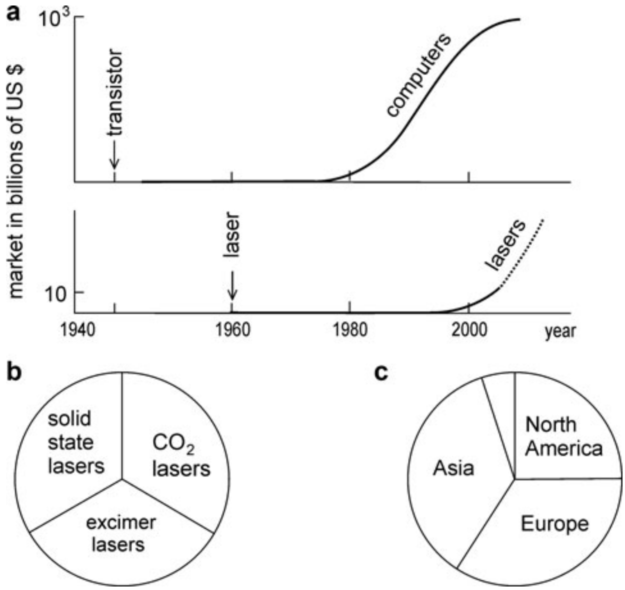

Fig. 1.3 Laser market. (**a**) General development. (**b**) Industrial lasers (in 2010). (**c**) Places of installation

(Fig. 1.3b) came from the CO_2 lasers, the excimer lasers, and the solid state lasers (including a small portion of semiconductor lasers). Among the solid state lasers, there are different types, namely rod lasers, disk lasers, and fiber lasers. Industrial lasers find use in material processing — cutting, welding, marking, engraving, and microprocessing. A main application of excimer lasers concerns structuring of semiconductors. The overall turnover of industrial lasers was about nine billion dollar in 2010. Most installations of industrial lasers (Fig. 1.3c) are in Asia, Europe, and North America.

Lasers are the basis of photonics (= photoelectronics) and optics. *Optoelectronics* — the counterpart at optical frequencies to electronics at radio and microwave frequencies — and *integrated optics* refer to optical systems used in optical communications, signal processing, sensing with radiation, and other fields. A characteristic of optoelectronics is the extension of methods of electronics to the range of optical frequencies.

Semiconductor lasers used in data communications and in consumer applications are produced at a rate of more than one million in a week (at a prize of about 1 U.S. $ per piece); these are mainly vertical-cavity surface-emitting lasers (Sect. 22.7). More than one million lasers per month are produced for the telecommunication market. The lasers for the telecommunication market have a higher level of sophistication and are produced in 2011 at a price of about $10 per piece; the lasers are edge-emitting lasers, especially distributed feedback lasers (Sects 20.5 and 25.4).

1.5 Questions About the Laser

In this book, we will treat a number of questions about the laser. Here we list some questions answered in different chapters of the book.

- What is common to all lasers?
  Answer: common to all lasers is the generation of radiation of high directionality; the generation is due to stimulated emission of radiation either by quantum systems such as atoms and molecules or by oscillating free electrons.
- What is the working principle of the free-electron laser?
- How can we generate monochromatic radiation?
- How can we generate femtosecond pulses?
- What is the role of diffraction in a laser? We will see that diffraction plays an important and favorable role: diffraction can suppress unwanted radiation.
- What is the angle of divergence of laser radiation? The angle of divergence is in general not determined by diffraction but by a kind of natural beams — Gaussian beams — that fit perfectly to resonators with two spherical mirrors. A laser is able to generate a Gaussian beam.
- How can we produce laser radiation in different ranges of the electromagnetic spectrum?
- What is the difference between a laser and a classical oscillator?

Laser physics connects optics with atomic physics, molecular physics, solid state physics (including semiconductor physics), and, of course, quantum mechanics, and furthermore with engineering, chemistry, biology, and medicine.

1.6 Different Types of Lasers in the Same Spectral Range

Why do we need different types of lasers for the same spectral range? Different types of lasers fulfill different tasks.

- If we need lasers for CD (compact disk) or blue ray players, semiconductor lasers, with small sizes and low power consumption, fulfill the task.
- To cut metal plates, a high power laser like the CO_2 laser is suited. The efficiency of conversion of electric power to radiation power of a CO_2 laser is large (larger than 10%).
- To generate femtosecond optical pulses, with durations from 100 fs to 5 fs, only few of the many lasers have appropriate properties. The most prominent femtosecond laser is the titanium–sapphire femtosecond laser.

Large progress came with the miniaturized semiconductor lasers but also with the high-power semiconductor lasers — that can be applied, for example, as pump sources of other lasers.

1.7 Concept of the Book

Figure 1.4 gives a survey of the main topics treated in the book.

General description of a laser and an example. We will describe main properties of a laser and of the components, namely the active medium and the resonator. We will introduce the laser as an oscillator: an active medium drives the oscillation of an electromagnetic field in a resonator. Early in the book we will discuss a particular laser (the titanium–sapphire laser) in some detail. This allows us to be specific, if

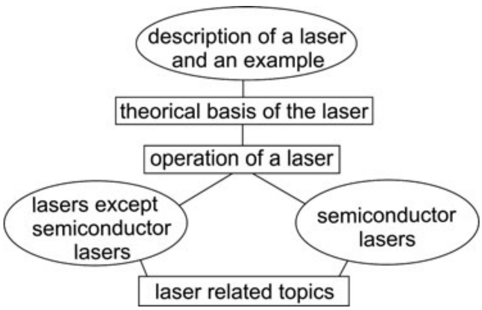

Fig. 1.4 Concept of the book

necessary, during a treatment of the theory and the discussion of the operation of a laser.

Theory of the laser. To describe the interaction of light with matter, we introduce the Einstein coefficients. A theoretical treatment of the laser oscillation yields the laser threshold condition and other important properties.

Operation of a laser. We will mention different techniques of operation of a laser as a continuous wave laser or as a pulsed laser. We will begin this part with a treatment of the properties of resonators and the description of Gaussian waves.

Lasers except semiconductor lasers

- Gas lasers. The active medium consists of atoms, ions, or molecules in gases. Gas lasers are available in the UV, visible, NIR, FIR, and microwave ranges. Two of the most important industrial lasers (the excimer and the CO_2 laser) are gas lasers.
- Solid state lasers (except semiconductor lasers). The active medium consists of ions in a dielectric solid; the solid is a host of ions. Solid state lasers, operated at room temperature, are available in the visible and the near infrared. Stimulated transitions between electronic states of ions give rise to generation of laser radiation. Beside crystals, other condensed matter materials — glasses, polymers, and liquids — are suited as host materials of ions, atoms, or molecules.
- Free-electron lasers. The basis is the emission of radiation by oscillating free electrons. The electrons are passing at a velocity near the speed of light through a spatially periodic magnetic field. Free-electron lasers are available in the visible, infrared, and far infrared; free-electron lasers generating X-rays are in a planning state.

Semiconductor lasers (bipolar semiconductor lasers and quantum cascade lasers). Semiconductor lasers are solid state lasers that make use of conduction electrons in semiconductors. Semiconductor lasers are available in the visible, near UV, and NIR spectral ranges and are being developed for the FIR. Stimulated transitions are either due to electronic transitions between the conduction band and the valence band of a semiconductor — in bipolar lasers — or between subbands of a conduction band — in quantum cascade lasers. Preparation of mixed semiconductor materials and of heterostructures makes it possible to realize new, artificial materials that are used in quantum well, quantum wire, quantum dot, and quantum cascade lasers. The laser wavelength is adjustable through an appropriate design of a heterostructure. We will, furthermore, present the idea of a *Bloch laser* (= superlattice Bloch laser = Bloch oscillator) that may become suitable for generation of FIR radiation.

Laser-related topics

- Optical communications. This is an important field of applications of semiconductor lasers.
- Light emitting diode (LED). The LED is the basis of many different kinds of illumination. The development of LEDs is going on in parallel to the development of semiconductor lasers. The organic LED (OLED) is suited to realize simple large area light sources.

- Nonlinear optics. We will give a short introduction to the field of nonlinear optics. Our main aspect will be: how can we convert coherent laser radiation of one frequency to coherent radiation of other frequencies?

We will discuss various applications in connection with different topics.

1.8 References

References cited either at the end of a chapter or in the text include: textbooks on lasers; textbooks on optoelectronics and integrated optics; books on lasers and nonlinear optics; textbooks on other fields (optics, electromagnetism, atomic and molecular physics, quantum mechanics, solid state physics; microwave electronics, mathematical formulas; and to a small extent original literature). Original literature about lasers is well documented in different textbooks on lasers [1–11]. Introductions to quantum optics are given, for instance, in [12, 13]. In connection with mathematical functions, see, for instance, [14–20].

1.9 A Remark about the History of the Laser

Data concerning the history of lasers

1865 James Clerk Maxwell (King's College, London): Maxwell's equations.

1888 Heinrich Hertz (University of Karlsruhe): generation and detection of electromagnetic waves.

1900 Max Planck (University of Berlin): quantization of radiation in a cavity.

1905 Albert Einstein (Patent office Bern): quantization of radiation.

1905 Niels Bohr (University of Copenhagen): quantization of the energy states of an atom.

1917 Einstein (then in Berlin): interaction of radiation with an atom; spontaneous and stimulated emission.

1923 Henryk A. Kramers: influence of stimulated emission on the refractive index of atomic gases containing excited atoms.

1928 Rudolf Ladenburg (Kaiser Wilhelm Institute, Berlin): observation of an influence of stimulated emission on the refractive index of a gas of neon atoms excited by electron collisions in a gas discharge.

1951 Charles H. Townes (Columbia University): idea of a maser.

1954 Townes: ammonia maser (frequency 23.870 GHz, wavelength 1.25 cm); Nicolai Basov, Aleksandr Prokhorov (Lebedev Physical Institute, Moscow): idea of a maser in parallel to the development in the U.S.A and realization of an ammonia laser.

1956 Nicolaas Bloembergen (Harvard University): proposal of the three-level maser (leading to solid state masers in other laboratories).

1958 Arthur L. Schawlow, Townes: proposal of infrared and optical masers (lasers) including the formulation of the threshold condition of laser oscillation; Prokhorov: general description of the principle of optical masers (lasers).
1959 Basov: proposal of the semiconductor laser.
1960 Theodore Maiman (Hughes Research Laboratories): ruby laser (694 nm).
1960 Ali Javan (Bell laboratories): helium-neon laser (1.15 μm, later 633 nm).
1961 L. F. Johnson, K. Nassau (Bell Laboratories): neodymium YAG laser.
1962 Robert N. Hall (General Electric Research Laboratories): semiconductor laser.
1963 Herbert Kroemer (University of California Santa Barbara): proposal of the heterostrucure laser.
1964 C. Kumar N. Patel (Bell Laboratories): carbon dioxide laser; W. Bridges (Bell Laboratories): argon ion laser.
1966 Peter P. Sorokin (IBM Yorktown Heights) and Fritz P. Schäfer (Max-Planck-Institut für Biophysikalische Chemie, Göttingen): dye laser.
1968 William T. Silfvast (Bell Laboratories): metal vapor laser.
1975 Basov: excimer laser.
1977 John Madey, Luis Elias and coworkers (Stanford University): free-electron laser.
1979 J. C. Walling (Allied Chemical Corporation): alexandrite laser (first tunable solid state laser).
1982 P. Moulton (Schwartz Electro-Optics): titanium-sapphire laser.
1991 M. Haase and coworkers (3M Photonics): green diode laser (based on ZnSe).
1994 Federico Capasso, Jérome Faist and coworkers (Bell laboratories): quantum cascade laser.
1997 Shuji Nakamura and coworkers (Nichia Chemicals, Japan): blue diode laser (based on GaN).

For references concerning the history of lasers, see [21–25] and also Sects. 9.10 and 19.13. The acronym laser was introduced by Gordon Gould (Columbia University) at the Ann Arbor Conference on Optical Pumping in 1959. In his thesis (Moscow 1940 – unknown until 1959) Vladimir Fabrikant proposed amplification of optical radiation by stimulated emission of radiation.

In 1951, Charles Townes, searching for an oscillator generating microwave radiation at higher frequencies than other microwave oscillators (magnetron, klystron) available at the time, had the idea of a maser [22] – based on three aspects (see Sect. 4.1): stimulated emission of radiation by an atomic system; creation of a population inversion (in a molecular beam); feedback of radiation by use of a resonator. The realization of the first maser (1954) stimulated the development of other types of masers, particularly of the solid state three-level maser. In 1958, Schawlow and Townes published an article on "infrared and optical masers." This paper described the conditions of operation of a laser (Chap. 8) and initiated the search for a concrete laser. Maiman was the first to operate a laser, the ruby laser, in Mai 1960. Later in the year, Javan reported operation of a helium–neon laser.

The application for a laser patent in mid-1958 by Bell Laboratories, with Schawlow (at Bell Laboratories) and Townes (Columbia University) as inventors, led to the first U.S. patent on a laser, issued in 1960. Gordon Gould, then working in a group at Columbia University on his PhD thesis, wrote in several notebooks (from 1958 on after the circulation of preprints of the 1958 paper of Schawlow and Townes) ideas about lasers, which later were the basis of patent applications. After many court cases, Gould succeeded to obtain patents on various aspects of lasers. Since it took a very long time to be issued (in 1976, 1978, 1988, and 1989), the patents allowed Gould and several companies he co-founded to get back the money (several tens of millions of dollar). For this purpose, laser companies were forced by further court cases to pay license fee.

The theoretical basis of the laser was the "old quantum mechanics" developed (1900–1917) by Planck, Bohr, and Einstein. The main results of the old quantum mechanics obtained a consequent founding by the quantum mechanics (developed 1925–1928). Why did it last about 40 years until maser and laser were operating? This question will be discussed in Sect. 9.10.

Nobel Prizes in the field of lasers

1964	Charles Townes, Nicolay Basov, Aleksandr Prokhorov: fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle.
1966	Alfred Kastler: optical pumping.
1971	Dennis Gabor: holography.
1981	Nicolas Bloembergen, Arthur Schawlow: nonlinear optics and laser spectroscopy.
1989	Norman F. Ramsey: maser and atomic clocks.
1997	Steven Chu, Claude Cohen-Tannoudji, William D. Phillips: methods of cooling and trapping of atoms by use of laser light.
1999	Ahmed Zewail (Chemistry): study of chemical reactions by use of femtosecond laser pulses.
2000	Zhores Alferov, Herbert Kroemer: semiconductor heterostructures – the basis of lasers of high-speed opto-electronics.
2001	Wolfgang Ketterle, Eric Cornell, Carl Wieman: experimental realization of Bose Einstein condensation.
2002	John B. Fenn, Koichi Tanaka (chemistry); mass spectroscopic analysis of biomolecules by use of laser desorption.
2005	Roy Glauber: theory of coherence (the basis of modern quantum optics); Theodor Hänsch, John Hull: optical frequency analyzer.

2009 Charles K. Kao: ground braking achievements concerning the transmission of light in fibers of optical communications; Willard S. Boyle, George E. Smith: invention of an imaging semiconductor circuit – the CCD sensor.

Problems

1.1. Physical constants. Remember numerical values of physical constants (in units of the international system, SI).

(a) c = speed of light.
(b) h = Planck's constant.
(c) $\hbar = h/(2\pi)$.
(d) e = elementary charge.
(e) m_0 = electron mass.
(f) μ_0 = magnetic field constant.
(g) ϵ_0 = electric field constant.
(h) k = Boltzmann's constant.
(i) N_A = Avogadro's number.
(j) R = gas constant.
(k) L_0 = Loschmidt's number.
[*Hint*: in examples in the text and in the Problems, an accuracy of several percent of a quantity is in most cases appropriate.]

1.2. Frequency, wavelength, wavenumber, and energy scale. It is helpful to characterize a radiation field on different scales: frequency ν; wavelength λ; wave number $\tilde{\nu} = \nu/c = 1/\lambda$ (= number of wavelengths per unit of length = spatial frequency); and photon energy $h\nu$ in units of Joule or eV. Express each of the following values by the corresponding values on the three other scales.

(a) $\lambda = 1\,\mu$m.
(b) $\nu = 1$ THz.
(c) $\lambda = 1$ nm.
(d) $\tilde{\nu} = 1\,\text{m}^{-1}$.
(e) $h\nu = 1$ eV.

1.3. Express the following values on different scales:

(a) kT for $T = 300$ K (T = temperature); (b) 1 meV; (c) $1\,\text{cm}^{-1}$; (d) $10\,\text{cm}^{-1}$.

1.4. Power of the sun light and of laser radiation. The intensity of the sun light on earth (or slightly outside the atmosphere of the earth) is 1,366 W m^{-2}.

(a) Evaluate the power within an area of $1\,\text{cm}^2$.
(b) Estimate the power density (= intensity) if the radiation incident on an area of $1\,\text{cm}^2$ is focused to an area of 100 μm in diameter; focusing to a smaller

diameter is not possible because of the divergence (5 mrad) of the radiation from the sun.

(c) Determine the power density of the radiation of a helium-neon laser (power 1 mW, cross sectional area 1 cm^2) focused to an area that has a diameter of 1 μm.

1.5. Determine the time it takes light pulses to travel different distances.

(a) A distance that corresponds to the diameter of an atom.
(b) A distance of 1 cm.
(c) From a point of the surface of the earth to a point on the surface of the moon (at a distance of about 174,000 km).

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