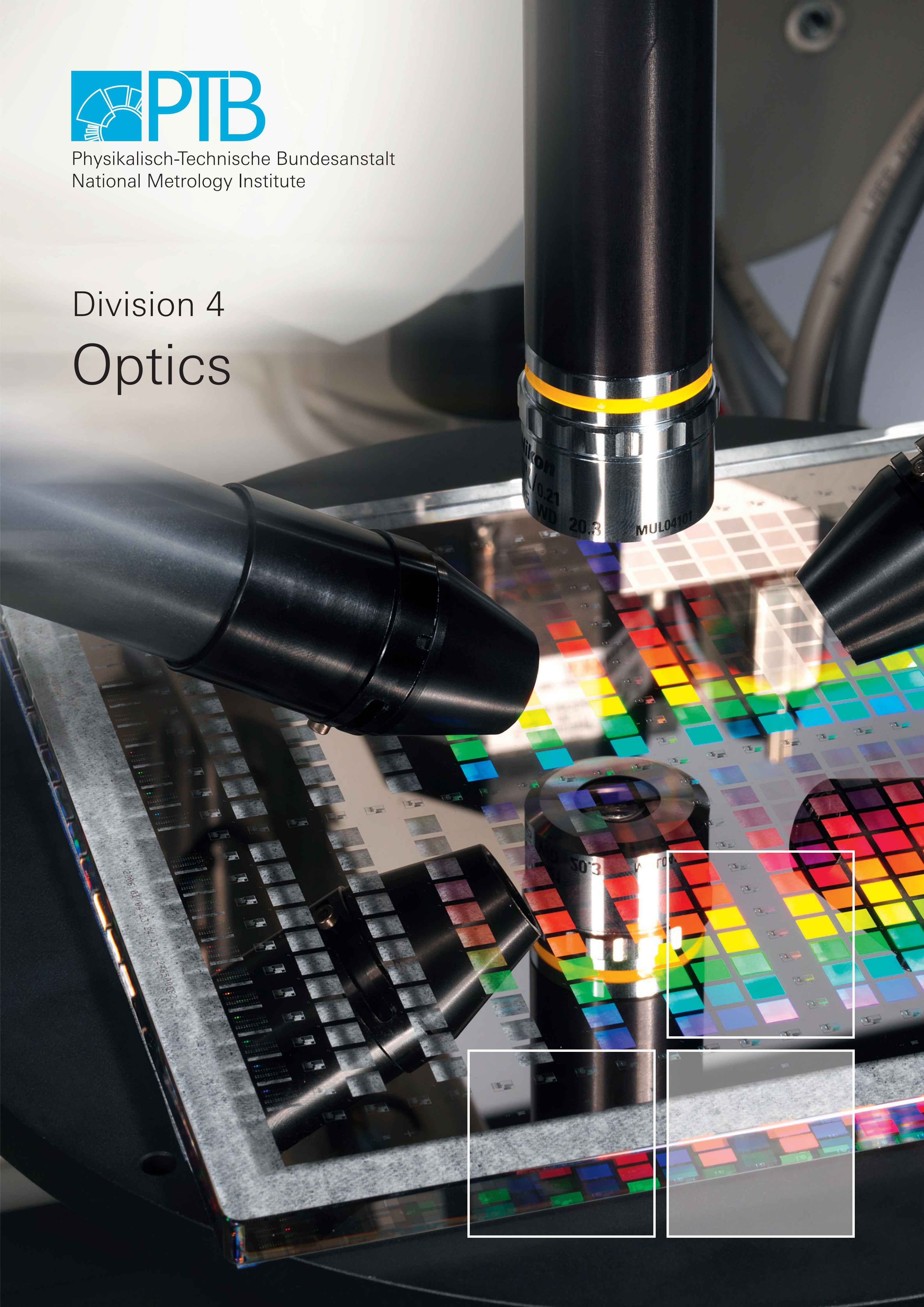
Physikalisch-Technische Bundesanstalt
National Metrology Institute

Division 4

Optics



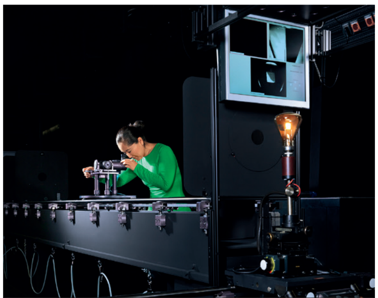
Optics

What time is it? How long is one meter? How bright is an LED? And also: How strong is a laser, how do I measure individual light particles, how smooth is a mirror and how good is a lens? How do I measure the height difference between two places which are far away from each other? And are the fundamental constants actually constant? With the aid of modern optical methods, the Optics Division provides precise answers to these and many other questions.

Photometry and Radiometry

The Candela

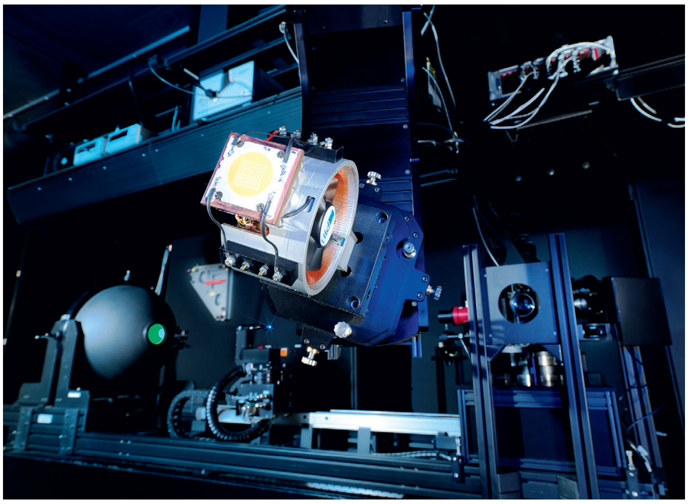
The candela[1] is the unit of luminous intensity. At PTB, the candela is realized by means of spectrally characterized photometers and maintained by a network of calibrated special incandescent lamps. At the same time, intensive work is being performed on an improved radiometric realization. For this purpose, a special detector is being developed which makes the transition from radiometric radiation power to the sensitivity of the human eye almost ideal. A universal photometer bench system (more than 40 m in length) allows all directional photometric quantities to be determined with a small measurement uncertainty.



Section of the 42 m long photometer bench used for the realization and dissemination of the SI base unit "candela". In the foreground, a luminous intensity standard lamp is operated whose mechanical orientation is being checked.

Photometry

Photometry deals with measurements in the spectral range of visible light which are evaluated by means of the sensitivity of the human eye. It is thus a significant field of metrology and is closely connected to the needs of industry and society. For technical and industrial applications, photometric quantities derived from the unit of luminous intensity, the candela, are appropriate. The economically most important quantity in the field of lighting technology is the luminous flux with its unit lumen (lm). It is a measure for the entire visible radiation emitted by a source and is thus evaluated by the sensitivity of the human eye. The luminous flux is used, among other quantities, to quantitatively describe the energy efficiency of lamps. At PTB, it is measured with the aid of a robot goniophotometer and an integrating sphere. Other important quantities that can be found in many standards are the illuminance with its unit lux (lx), and the luminance (cd/m^2). The latter is used, for example, to characterize displays. At PTB, also novel light sources such as large-area organic light-emitting diodes (OLEDs) or high-performance LEDs can be measured with regard to their color and their directional characteristics by means of camera- and robot-supported measuring techniques. In photometry, spectrally resolved measuring techniques have become increasingly established and the integral photometric quantities are determined mathematically on the basis of these measuring techniques.



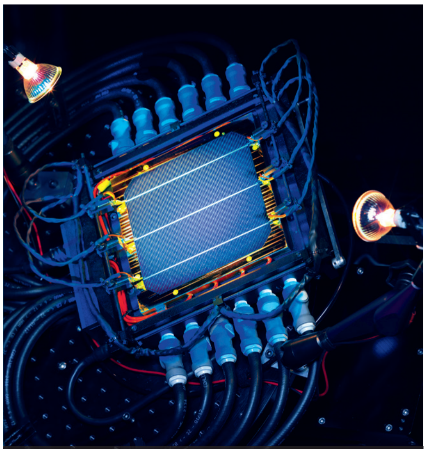
Measuring set-up for the calibration of LED standards for the quantities of luminous flux, luminous intensity, spectral distribution and all colorimetric parameters derived from them.

Radiometry

Radiometry deals with the measurement of electromagnetic radiation. PTB is concerned with several subareas of radiometry.

Spectroradiometry deals with the realization, maintenance and dissemination of the radiometric unit of spectral irradiance in the spectral range of 200 nm to 2500 nm. Current main research activities are related to the measuring of high UV irradiances (e.g. for water disinfection and paint curing) as well as the traceability for measuring terrestrial solar UV radiation to determine the atmosphere's ozone content.

[1] The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit $lm\,W^{-1}$, which is equal to $cd\,sr\,W^{-1}$, or $cd\,sr\,kg^{-1}\,m^{-2}\,s^3$, where the kilogram, meter and second are defined in terms of h, c, and $\Delta\nu_{Cs}$. (9th SI Brochure)



Industrial solar cell; its efficiency is determined in dependence of the light spectrum and of the irradiation direction. The results are needed for energy rating calculations.

The interaction of radiation with solid material and surfaces is described by transmittance and reflectance. These quantities are transferred by calibrated standards to a wide span of optical measurement applications. For example, measurement device manufacturers, the paint and coatings industry, medical applications, as well as the sugar industry and exhaustive gas measurement benefit from the service offered for a broad spectral range from the ultraviolet to the infrared. Highly specialized devices like gonioreflectometers are available for versatile measurement tasks.

PTB is continuously extending its portfolio in the field of photovoltaics and is setting up a competence center for PV metrology to support this important pillar of Germany's energy transition. PTB is one of only a few reference laboratories worldwide which ensure the international equivalence of the measurement results in photovoltaics. A novel laser-based measuring facility does not only allow measurements with the lowest measurement uncertainty worldwide, but it also opens up completely new possibilities to characterize solar cells with regard to their spectral and angle-resolved properties. Furthermore, metrology as well as the field of outdoor calibration are constantly being enhanced, also regarding the use of solar simulators for solar cell and solar module calibration.

In the field of laser radiometry, PTB's facilities allow the calibration of laser power meters for several wavelengths and optical powers that are relevant to industry. The wavelength range and the optical power range currently covered are from 193 nm to 10.6 µm, and from a few microwatts to two kilowatts, respectively. The optical power meters can be calibrated for continuous and for pulsed lasers. A special field consists of the calibration of detectors for optical communication at 850 nm, 1.3 µm and 1.55 µm which are connected directly to an optical fiber.

In addition, the Optics Division intensively conducts research in the field of quantum radiometry. This field deals with the defined generation of single light particles which are emitted separated in time, as well as with their precise measurement. Currently, traceable single-photon sources are being developed with regard to their use as quantum-based standard sources for radiometry. A modern test assembly makes it possible to traceably calibrate single-photon detectors at photon fluxes down to 1,000 photons per second. Other important applications for these novel sources and detectors include quantum cryptography and quantum communication.

Time and Frequency

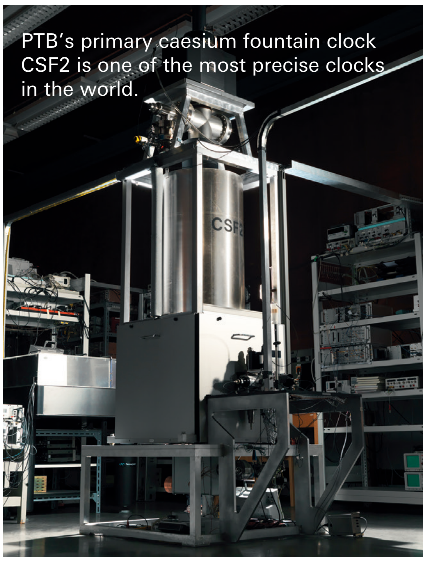
The Second

As long ago as in 1967, the unit of time, the "second", was defined on the basis of an atomic natural constant. According to that definition, the second is the duration of 9 192 631 770 periods of the microwave radiation corresponding to the transition between the two ground-state levels of caesium (^{133}Cs)[2]. Gone are the times when the second was defined as a fraction (1/86400) of a "mean solar day" and thus was not known more precisely than a relative $1 \cdot 10^{-8}$. Today, the best atomic clocks are by eight orders of magnitude more precise; no other SI unit can be realized with a similarly small uncertainty.

In Germany, PTB has been entrusted with the realization and dissemination of the unit of time by the Units and Time Act. For that purpose, PTB's Optics Division operates four primary caesium atomic clocks from which legal time is derived in Germany.

The most precise clocks are the two so-called caesium fountain clocks CSF1 and CSF2 (in operation since 1999 and 2009, respectively), working with laser-cooled caesium atoms. These atomic clocks are used to realize the unit of time, the "second", with an uncertainty of approximately $3 \cdot 10^{-16}$. This corresponds to a precision of one second in 130 million years. The older caesium atomic clocks CS1 and CS2 (in operation since 1969 and 1986, respectively) work with a caesium atomic beam and achieve a precision of "only" one second in 3 million years.

With its primary atomic clocks and their outstanding precision, PTB – in cooperation with 70 other time-keeping institutes – contributes to the realization of UTC. UTC stands for "Coordinated Universal Time" and is the guideline according to which national time scales, e.g. UTC(PTB) for Germany, are adjusted every month. When realizing the exact time, PTB cooperates with the other time-keeping institutes. To be able to compare clocks worldwide, various techniques are used: signals received from satellite navigation systems such as GPS, GLONASS and Galileo along with the exchange of time signals via TV satellites and fiber-optic networks.



PTB's primary caesium fountain clock CSF2 is one of the most precise clocks in the world.

[2] The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}. (9[th] SI Brochure)

Dissemination of Time

Central European Time (CET) – the legal time in Germany – is determined by adding one hour to Coordinated Universal Time which is realized at PTB by caesium atomic clocks and named UTC(PTB). Central European Summer Time (CEST) is observed between the last Sunday of March and the last Sunday of October by adding 2 hours to UTC(PTB).

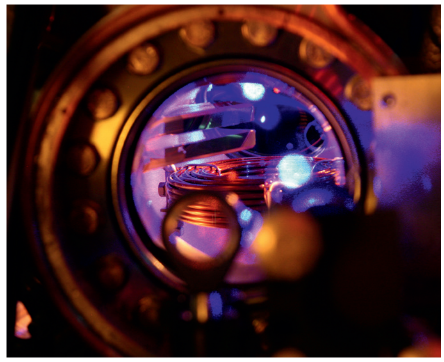
The dissemination of time is realized in three different ways. The long-wave transmitter DCF77 of Media Broadcast GmbH in Mainflingen emits time signals. They can be used within a range of approximately 2000 km of the transmitter to control radio-controlled clocks. During each minute, the numbers of the minute, hour, calendar day, day of the week, calendar month and the two last digits of the calendar year are transmitted. For this purpose, the second markers are encoded by means of pulse-width modulation. The control signal, which is generated at the place of transmission by means of a control facility developed by PTB, is controlled from Braunschweig. In this way, approximately 100 million radio-controlled clocks throughout Europe are provided with the correct time. In most cases, it is sufficient for these clocks to indicate the "correct" second. Energy providers, telecommunication companies, air-traffic control, services and many others synchronize their clocks with the DCF77 signal with a precision of much better than a millisecond, in which the propagation delay of the signal is considered. Furthermore, time is disseminated with similar precision via the public telephone network. Over time, the internet has become more and more important as a medium to disseminate time: At PTB, three servers attend to approximately 600 million requests daily with the aid of Network Time Protocol.

Optical Atomic Clocks

In the case of clocks, the precision and frequency stability usually increase with a higher frequency of the "pendulum" of the clock. For a caesium atomic clock, the frequency lies in the microwave range, and for optical clocks – in which case lasers excite transitions in atoms or ions – the frequencies are in the range of visible light. From the frequency of the optical clocks that are currently being developed (which is higher by approximately five orders of magnitude), a clear improvement of the precision is expected as compared to caesium atomic clocks.

Research is being carried out in the Optics Division to find various possibilities of realizing an optical clock. As there are various research approaches on the route to the best atomic clock, for example optical transitions in $^{171}Yb^+$ or $^{27}Al^+$ single ions, in the ^{229}Th nucleus and in neutral ^{87}Sr atoms which are arranged in an optical lattice are being investigated.

Optical clocks became possible only after the methods of high-resolution laser spectroscopy, the technology of laser cooling of ions and atoms, and frequency measurements with optical frequency combs had been invented. Nowadays, the high frequency of optical clocks in the petahertz range (10^{15} Hz) can only be measured in a relatively easy way by means of frequency combs generated via femtosecond lasers. All these techniques are further refined, advanced and applied in a series of experiments at the Optics Division. The high precision achieved so far even makes it possible to put fundamental theories of physics under test and thus to find an answer to the fundamental question of "How constant are certain natural constants?", which is still unanswered.



View into PTB's strontium lattice clock: approximately one million strontium atoms are cooled down very close to the absolute zero point with the aid of laser light. The blue laser beams localize the atomic cloud in the vacuum vessel, whereby the atoms are excited to blue fluorescence (center of photo).

Length and Dimensional Metrology

The Meter

Set-up for the realization of the meter by means of iodine-stabilized lasers.

The definition of the meter from the year 1983[3] and its revised version from 2019[4] link the unit "meter" with the unit "second" via the definition of the fundamental natural constant "speed of light in vacuum" (c = 299 792 458 m/s). With this definition, the general metrological tendency to refrain from insufficiently stable and exact artefacts and to define units based on natural constants was continued. The meter thus belongs to the field of optics, with a close connection to exact time and frequency measurements.

By means of a frequency comb, an optical frequency can be traced directly to the same primary caesium atomic clock which is also used to realize the second. At PTB, iodine-stabilized lasers with accurately known frequency are used to realize the unit of length. Using optical interferometric techniques, these lasers enable traceable length measurements at the highest level of accuracy which are not limited by the frequency uncertainty of the reference lasers.

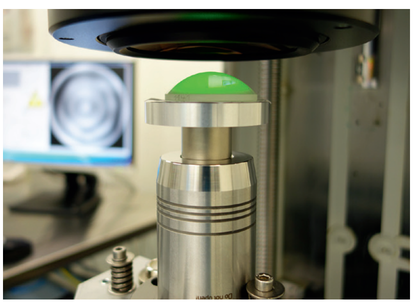
[3] The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

[4] The meter, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{Cs}$. (9th SI Brochure)

To disseminate the unit of length, the wavelengths of stabilized lasers of customers from the fields of industry and research are calibrated by comparing them with the wavelength standards of PTB or by means of optical frequency measurement via a frequency comb.

Optical Form Measurement

Optical surfaces manufactured with high precision are indispensable for many applications in technology and science. This extends from the small lenses for cell phone cameras, varifocal spectacle lenses and optical systems manufactured with the highest precision for photolithography (for the manufacture of computer chips), to very large mirrors which are, for example, used in synchrotrons for beam deflection or in astronomical telescopes. A prerequisite for the manufacture of these high-precision surfaces is a – correspondingly precise – measurement. The flat surfaces currently require measurement uncertainties of only a few nanometers. A measurement procedure which has been developed at PTB for these extreme accuracies utilizes the known law of optical reflection and the linear propagation of light as a natural, high-precision reference. Smooth, reflecting flats or spherical surfaces can also be optically scanned and determined by means of interferometers. Here, PTB calibrates reference surfaces for industry. Current research activities are aimed at also measuring more complex surface forms, e.g. aspherical lenses and surfaces of arbitrary form, with a high precision. In addition, new measurement procedures are being developed for the traceable measurement of optical wave fronts. The research and development work is being carried out in close cooperation with other PTB departments and external partners.



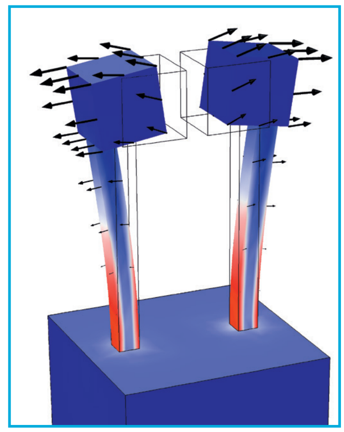
Optical form measurement with the aid of the tilted-wave interferometer.

Optical Nanometrology

Nanostructures have long since established themselves in our daily lives. The components of modern electronic systems are, for example, composed of structures which have, in part, only a size of a few 10 nanometers. In the production process, they must be manufactured and measured with a precision of a few nanometers. As such structures are clearly smaller than the wavelength of the light used for the measurement, the conventional microscopic procedures reach their limits here. For accurately measuring the geometry of periodic structures, the surface is illuminated with a laser. The angular distribution and the intensities of the scattered light allow the size and the form of the grating structures to be determined. With the aid of this technology, grating structures can be measured without an imaging objective. This procedure can also be used for lattice structures with lattice periods below half the wavelength: Although no diffraction takes place in these cases, the structure sizes can be determined from the polarization-dependent reflection characteristics. In this way, PTB is well prepared for future tasks of industry and for the ever-finer structures of the new chip technology.

Metrology for Functional Nanosystems

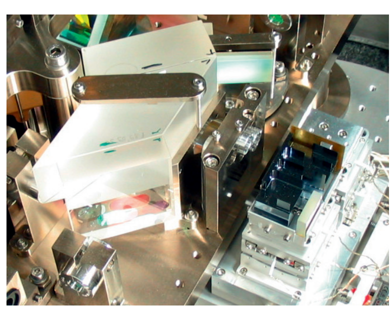
Nanoscale systems with structural dimensions of a few 10 nm to a few 100 nm allow optical characteristics and functionalities which cannot be accessed by means of macroscopic systems. For example, nanostructures can be used to increase the effective traveling time of light in matter by far. The Junior Research Group "Metrology for Functional Nanosystems" investigates functional nanooptical systems for applications in sensor technology and high-precision metrology. Focal points are, on the one hand, the increase of the interaction between light and matter for optical measuring systems (e.g. polarimetry) and dimensional metrology. On the other hand, low-noise micro- and nanooptical systems for optical high-precision metrology and relevant material properties, e.g. mechanical losses, photoelasticity and thermal conductivity in nanosystems, will be examined.



Mechanical deformation induced by the radiation force for light modulation in silicon nanostructures with a high aspect ratio.

X-ray Optics

X-rays have a much shorter wavelength than visible light and can penetrate matter. They are, thus, ideally suited to measure ultra-short distances inside solids. With so-called X-ray interferometers, the distance of the atoms in the crystal lattice or the wavelength of X-radiation can be indicated directly in the unit of length, the "meter", whereby the measurement uncertainty is not larger



PTB's combined X-ray and optical interferometer for the measurement of the lattice parameter of isotopically enriched silicon-28.

than one billionth part of the distance of two atoms in the solid. This measurement technology has provided findings on the atomic structure of silicon crystals which were necessary to determine the Avogadro constant by means of the so-called "crystal density method" and thus eventually to determine Planck's constant, which is a crucial prerequisite for the redefinition of the kilogram. The last primary standard based on an artefact has thereby also been replaced by a definition via a natural constant. With its measurement technology, the Optics Division has contributed, among other things, to the precise determination of the distance of atoms in an isotopically enriched ultrapure silicon-28 sphere.

The Optics Division

In the Optics Division, three of the seven base units of the International System of Units (SI) are realized, maintained and disseminated: the "candela" (cd, luminous intensity, the "second" (s, unit of time) and the "meter" (m, unit of length). With the UTC(PTB) time scale, the Division realizes the basis of legal time in Germany. In the field of optical metrology, the standards are measured with the highest precision and made available to the customer in a reliable and economic way. Within the scope of national and international projects, the Division works with other metrological institutes, universities and research institutions and cooperates in certification and international standardization.

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Federal Ministry
for Economic Affairs
and Energy

The Physikalisch-Technische Bundesanstalt, Germany's national metrology institute, is a scientific and technical higher federal authority falling within the competence of the Federal Ministry for Economic Affairs and Energy.

Photo Cover: Ellipsometry on structured surfaces (lattice structures). The lattice periods are between 320 nm and 520 nm, so that diffraction colors are visible. (PTB)