PTB news
Scientific Newsletter
2
2022

Three times a year, PTB News provides topical information from the varied spectrum of activities of the Physikalisch-Technische Bundesanstalt (PTB) consisting of fundamental research, legal metrology and PTB's various activities in the service of the economy.

SCIENTIFIC NEWS

TECHNOLOGY TRANSFER

MISCELLANEOUS

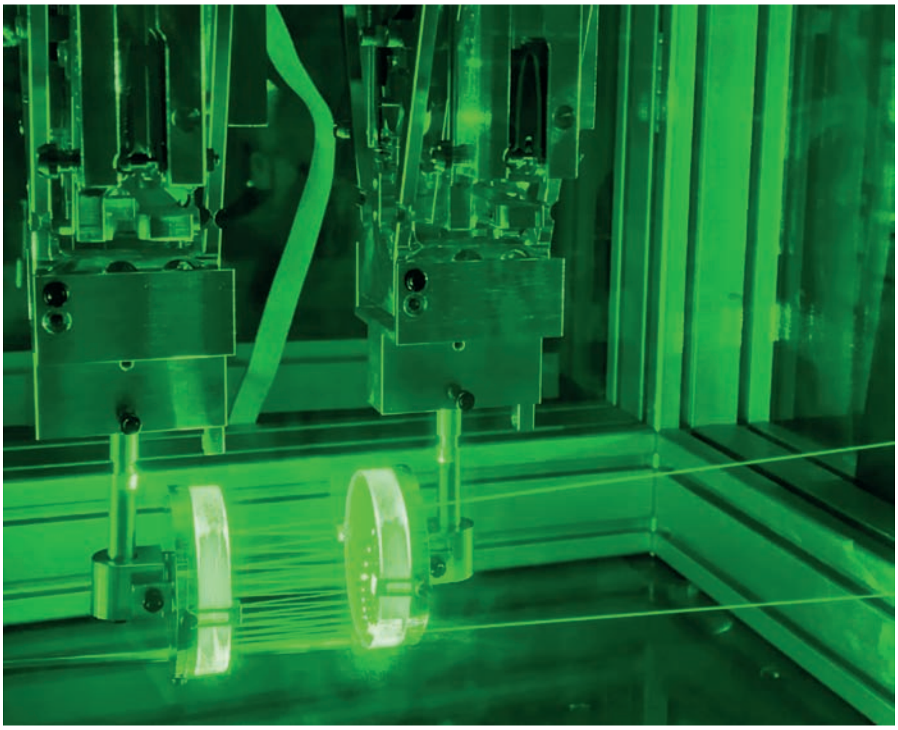
Photon momentum for metrology

Optical power measurements by means of radiation force

Especially interesting for
- radiometry
- mass and force measurement
- astrophysics

In the past few years, increasing attention has been paid to the use of photon momenta in metrology, mainly in the field of radiometry, but also in force and mass measurement. This is due to the fact that photons behave like particles. When they collide with matter, the resulting momentum transfer can be used for measuring optical power or, vice versa, for generating a small force. This method of optical power measurement has now been accurately compared with well-established measurement procedures.

Although a photon does not have a mass, it does carry momentum and energy proportional to the frequency and inversely proportional to the photon's wavelength. When a light beam consisting of a great number of photons hits a highly reflective mirror, most of these photons are reflected and only very few are absorbed. In both cases, the mirror recoils slightly due to this interaction. The major part of this recoil is generated by the reflected photons. This effect has been exploited in recent years for measuring high optical powers emitted by lasers. This method has a number of advantages compared to the traditional "thermal" approach: The measurement time is prospectively shorter, the device is more compact, and costs are lower. Moreover, the photon force transferred by lasers with a low optical power (in the



The optical cavity consists of two ultra-high-reflectivity mirrors (reflectivity > 99.995 %) that are suspended from two electromagnetic force-compensation balances. The visible laser beam is reflected 21 times between the mirrors.

mW range) can, in principle, be used for calibrating pico- and nanoforce measuring instruments (in the pN and nN ranges) or small masses, since this optical power can be measured very accurately by means of conventional thermal reference detectors.

PTB, in collaboration with the Technische Universität Ilmenau, has investigated the suitability and accuracy of this optical force measurement procedure based on photon momenta. A portable force measurement setup developed by the university was used for this purpose. This setup consists of two electromagnetic force-compensation balances and an optical cavity. The cavity is used to amplify the force by causing the mirrors to reflect the laser beam multiple times. The results of the optical power measurement using photon recoil have been compared with those obtained by means of a calibrated reference detector for an optical power range between 1 W and 10 W at a wavelength of 532 nm – which corresponds to a force of approx. 2 μN at an optical power of 10 W. The relative uncertainty of the force measurement was approx. 2.3 %, the average relative deviation between the two measurement methods was roughly 5 %.

Although the measurement uncertainties are currently still higher than those of the conventional method (approx. 1 %), this technique has a strong potential for measuring high optical powers in the kilowatt range, such as are required in industrial production, for instance. Applications are also encountered in fundamental research, e.g., in gravitational wave detectors. Here, the laser power used is factored directly into the determination of source distance and position. ▪

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Scientific publication
S. Vasilyan, M. Lopez, N. Rogge, M. Pastuschek, H. Lecher, E. Manske, S. Kück, T. Fröhlich: Revisiting the limits of photon momentum based optical power measurement method, employing the case of multi-reflected laser beam. Metrologia 58, 015006 (2021)

Optical constants in the EUV range

Creation of a database of materials for EUV lithography

Especially interesting for
• semiconductor industry

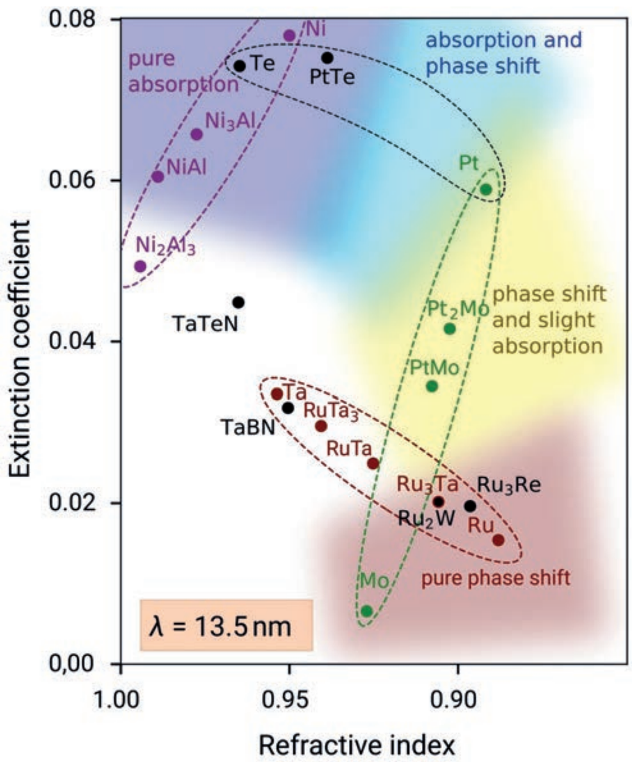
At PTB, optical thin-film materials for extreme ultraviolet lithography are systematically investigated at a wavelength of 13.5 nm. The optical constants (i.e., the refractive index and the extinction coefficient) have now been determined in the wavelength range between 10 nm and 20 nm with small uncertainties based on reflection measurements performed with synchrotron radiation.

Introducing EUV lithography into commercial semiconductor manufacturing has extended the spectral range of electromagnetic radiation used in industry to wavelengths of around 13.5 nm. To develop optical components such as mirrors, gratings or photomasks for this spectral range, it is essential to have accurate knowledge of the optical properties of the materials used. In the lithography process, an optical imaging system is used to demagnify and transfer the original image of the semiconductor structure from the photomask to the chip ingot.

The selection of materials is critical, in particular as regards the photomask: The achievable contrast of the image is largely determined by the beam attenuation and phase shift effects in the photomask itself. These effects depend very sensitively on the complex refractive index of the materials used.

For many chemical elements, existing databases of refractive indexes in the EUV range only contain estimations based on few measured values. The situation is obviously even worse when it comes to compounds.

Within the scope of EU-funded projects and long-term cooperation projects with research institutes and companies from the semiconductor sector, PTB has systematically investigated the optical properties of materials that are technologically relevant to EUV photomasks. These data can be used to search for and optimize new material systems in order to enhance the optical contrast of the structures to be imaged onto the semiconductor chips.



Extinction coefficient and refractive index of various materials for EUV lithography at a wavelength of 13.5 nm

The results for an initial set of 19 materials have now been published and thus made available for the purpose of technological development. For simple and fast retrieval, they have been made freely accessible as the cornerstone of a database to which new results are to be added continuously. ▪

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Link to the database
https://www.ocdb.ptb.de/home

Scientific publication
R. Ciesielski, Q. Saadeh, V. Philipsen, et al.: Determination of optical constants of thin films in the EUV. Appl. Opt. 61 (2022)

Fighting viruses in indoor air

DIN publication on the use of UV-C air purifiers, in particular in daycare centers and schools

Especially interesting for
- manufacturers, planners and testers of UV-C air purifiers

Which UV-C air purifier is effective against coronaviruses? Under which conditions? Are these devices safe to use? A publication developed by the DIN institute in collaboration with PTB ensures more safety for manufacturers, potential users and planners. Particular attention is paid to the safety of these devices, especially as concerns their use in schools or daycare facilities.

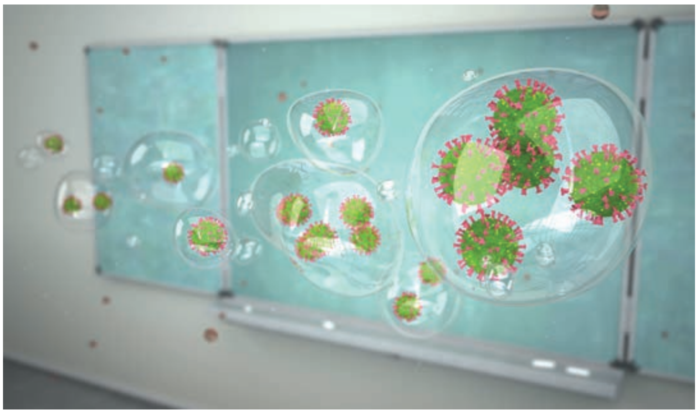
Coronaviruses are mainly passed on via aerosols, which makes them particularly dangerous in enclosed spaces. As studies have shown, UV-C air purifiers are able to reliably eliminate coronaviruses. If the air passing through the device is irradiated with a dose of approx. 70 J/m^2 of UV-C, it is possible to inactivate roughly 99 % of all airborne bacteria and viruses. Manufacturers and users of UV-C air purifiers therefore need to make sure that a sufficient dose of UV-C is delivered during a single passage.

The DIN/TS 67506 technical specification titled “Disinfection of room air with UV radiation – UV-C secondary air units” applies to devices featuring closed operation and active ventilation. It contains numerous technical details and method descriptions. Besides providing information on the effectiveness of devices, these details also address their efficiency in rooms of different sizes. The so-called hygienic air delivery rate (HADR) indicates how many cubic meters of disinfected air the device is able to produce hourly. In this way, it is possible to calculate the number of air renewals that are theoretically attainable to effectively reduce airborne germs for each room size and for each device.

An especially important aspect is that of safety, in particular protection from UV radiation. Devices must not cause harm to persons who remain in the immediate vicinity of a device for a longer period of time. A small amount of UV-C radiation may be emitted even by enclosed UV radiation sources. To minimize this amount, these devices should be designed such that they qualify for the Exempt risk group under EN 62471 “Photobiological safety of lamps and lamp systems”: The limit values stated in this standard refer to healthy adults and are specified on the basis of EU Directive 2006/25/EC such as to essentially rule out any hazard to people when devices are used as intended.

When operated near vulnerable persons, such as children or persons with existing eye or skin conditions, devices must emit no measurable UV radiation within the accessible area. According to the state of the art in metrology, this is the case if the UV irradiance in the spectral range from 200 nm to 300 nm at a distance of 20 cm from the device and up to a height of 180 cm from the ground does not exceed 200 µW/m^2 anywhere. This is also laid down very clearly in the technical specification.

When designed, tested and used according to the recommendations of DIN/TS 67506, UV-C air purifiers can contribute to fighting the pandemic. The next step will consist in developing a corresponding DIN standard based on this technical specification. ▪



Aerosols with coronaviruses in a classroom (symbolic picture: Adobe Stock/Alexander Limbach)

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The technical specification
DIN/TS 67506: Disinfection of room air with UV radiation – UV-C secondary air units. Beuth-Verlag, www.beuth.de

3D model for gears

Holistic characterization of helical machine elements

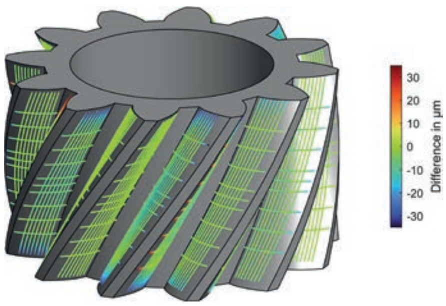
Especially interesting for
- manufacturers of gears and screw threads
- operators and manufacturers of coordinate measuring machines and evaluation software

In conventional gear and screw thread metrology, measurements for evaluating the quality of components are performed only pointwise or linewise in selected transverse and axial sections, respectively. In light of tighter manufacturing tolerances and new challenges brought on by modern production processes, this procedure is not sufficient. At PTB, a universal procedure has been developed to conduct areal measurements of helical machine elements and to evaluate them holistically by means of a parameterized 3D model.

Gears and screw threads of the most varied types are important components in all areas of mechanical engineering. Tight manufacturing tolerances define the requirements placed on the measuring equipment used for quality assurance purposes along the entire scale of quantities and across diverse sectors. To ensure that the evaluation of a component's quality is reliable and relevant to its function, the measurement processes used must be not only fast and accurate, but also, and most importantly, holistic. This means for one thing that the geometry must be acquired along all function surfaces and, for another, that all characteristics be evaluated in a single geometry element based on only one reference coordinate system.

Modern coordinate measurement systems provide areal information fast and reliably with regard to the dimension, form and position errors of helical machine elements. Up to now, however, standard evaluation procedures required reducing this data to individual lines. A major share of the data points thus had to be discarded. The new procedure enables the evaluation of areal measurement data distributed anywhere along the entire external surface. This procedure is based on a universal 3D model that allows helical machine elements to be described by means of a unique set of geometry parameters. The model is best-fitted into the data point cloud using a foot-point iteration algorithm. The actual values of the geometry parameters yielded in this way can then be converted into the determinants already established in conventional procedures.

It is planned to enhance this new procedure to characterize additional types of machine elements (such as those of bevel gears). Moreover, we are working to incorporate the procedure into standards in order to promote its use in industry. ▪



Best-fit 3D model illustrated on an involute gear. The data points are represented in false colors as residuals of this best-fit geometry.

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Scientific publication
M. Stein, F. Keller, A. Przyklenk: A unified theory for 3D gear and thread metrology. Appl. Sci. 11, 7611 (2021)

AI for the form measurement of optical surfaces

Deep neural networks for topography measurements with tilted-wave interferometers

Especially interesting for
- optical form measurement
- machine learning in optics

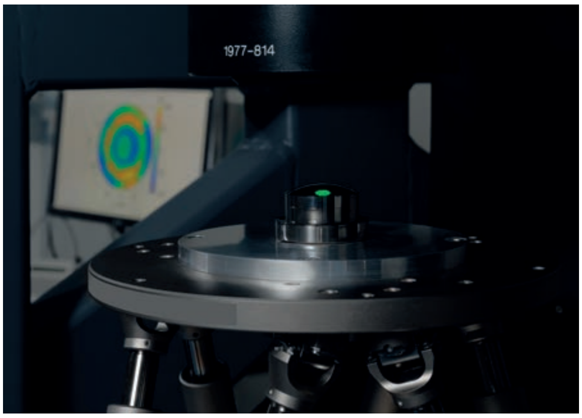
The highly accurate form measurement of optical aspheres and free-form surfaces represents a great challenge in metrology. A new method uses artificial intelligence (AI) – i.e., deep neural networks – to reconstruct optical surfaces from the measurement data of a tilted-wave interferometer. In addition, this method quantifies the uncertainty of the prediction.

Optical aspheres and free-form surfaces are widespread in industry. PTB, in cooperation with a partner from industry, has been doing research on how to enhance the tilted-wave interferometer – an interferometric measurement system used for the optical measurement of such surfaces – and perform traceable form measurement with the device. This device's reconstruction procedure is based on the comparison of the measurement data of the surface under test (SUT) with the simulated data of a design topography, i.e., with the expected form of the SUT. The deviation of the SUT from the design is then determined from the difference between the measurement data and the simulated data.

The new method exploits deep neural networks to determine this deviation. Using a set of several trained neural networks, the model uncertainty can also be reconstructed. In numerical experiments, it has been demonstrated that the method also provides reliable results even in the presence of calibration errors or noise.

The method was first applied to the measurement data of an aspherical SUT whose design topography has a base area diameter of approx. 25 mm and a maximum peak-to-valley value of approx. 4 mm. The reconstructed surface form is in agreement with the form reconstruction provided by a modern comparison method used in industry – their differences lie within the limits of the model uncertainties.

As soon as the neural networks have been trained, it is possible to assess new data at the push of a button. The method is thus fast and includes an uncertainty quantification of the prediction, making it potentially very interesting for use in mass production quality control and other future applications. ▪



Asphere being measured by means of the tilted-wave interferometer. The screen in the background displays the difference between the measured SUT and the expected design topography.

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Scientific publication
L. Hoffmann, I. Fortmeier, C. Elster: Uncertainty quantification by ensemble learning for computational optical form measurements. Machine Learning: Science and Technology 2, 035030 (2021)

An optical clock for end-users

Single-ion clock demonstrates robust operation

Especially interesting for
- astronomic observatories
- telecommunications network operators
- time laboratories

Due to their higher reference frequency, optical clocks enable measurements that are even more accurate than those of conventional atomic clocks. Until now, however, optical clocks could only be operated by experts in special laboratories. Within the scope of Opticlock, an industry-led pilot project for quantum technologies, a demonstrator of an optical clock has been built. This demonstrator makes the advantages of modern quantum technologies available to end-users in the form of a user-friendly device.

In optical clocks, transitions of trapped atoms or ions are driven by laser radiation. During operation, the frequency of the clock laser is tuned to exactly match the resonance frequency and can then be counted as the clock's beat. This frequency is about 100 000 times higher than the microwave frequency used to define the second, the SI base unit of time. Optical atomic clocks have been investigated in many specialized laboratories around the world to demonstrate the improvements attained due to the considerably higher frequency of optical laser radiation. However, it was previously not possible to operate such systems continuously over a longer period of time or to make them utilizable for operators who did not have a profound knowledge of the clocks' design. Such optical clocks could be particularly interesting for astronomic observatories and telecommunications network operators who have high system time stability requirements.

Within the scope of a pilot project on quantum technologies funded by the German Federal Ministry of Education and Research (BMBF), six companies, two universities and two research institutes, including PTB, pooled their expertise. Within three years, they succeeded in building an atomic clock demonstrator that is accommodated in two 19″ server rack cabinets. A reference transition of a single ytterbium ion stored in a radiofrequency ion trap defines the clock rate. All sub-components were optimized for the setup to exhibit best possible reliability

Demonstrator of an optical clock for end-users. The cabinet on the left contains control hardware and electronics. The cabinet on the right-hand side accommodates all lasers and optical setups as well as a wavelength measuring instrument and the ion trap.

and thus ensure robust operation. Several optimization and adjustment routines, which previously had to be made by scientific staff in the lab, have been automated. This not only reduces the demands placed on users of such a clock. The much faster execution minimizes the intervals in which the optical clock does not operate with the highest accuracy.

In a two-week measurement campaign, the optical clock demonstrated its ability to run robustly in continuous operation. Its atomic reference was exploited for 99.8 % of its total operating time. In the remaining time, automatic routines were performed to ensure maximum accuracy. There were no unwanted interruptions of operation and no malfunctions. The estimated timing error after two weeks was smaller than 15 picoseconds. Opticlock thus outperforms commercially available atomic clocks by a factor of 10. The system is to be made available for measurements on operators' sites and to contribute to the international atomic time scale at PTB. ▪

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Scientific publication
J. Stuhler, M. Abdel Hafiz, B. Arar, A. Bawamia, K. Bergner, M. Biethahn, S. Brakhane, A. Didier, J. Fortágh, M. Halder et al.: Opticlock: Transportable and easy-to-operate optical single-ion clock. Measurement: Sensors 18, 100264 (2021)

Mobile measuring system for electric vehicle charging stations

Measurement technology for real-world validation of conformity assessments for charging stations

Especially interesting for
- electromobility
- legal metrology

German government planning foresees the installation of one million public charging stations for electric vehicles in Germany by 2030. Whereas the correct metering and billing of fuel is reliable and a matter of course at conventional filling stations, the measurement technology used in particular for fast charging stations is still new and constantly being improved. A mobile measuring system allows those charging stations already in place to be checked in the field.

Before being granted approval, charging stations must first pass a type examination confirming that they are fit for purpose. This is done in the controlled environment of a laboratory. Flawless specimens of the approved type obtain a certificate allowing them to be placed on the market and to bill energy in kWh. Subsequent tests in routine operation in the field on carparks or at filling stations, however, are a challenge. Not only environmental factors such as temperature and weather conditions, but also the sheer number of different types of electric vehicles with their different charging behaviors place particular demands on the electric measuring equipment.

PTB has developed a precise measuring system specifically for this application. It is inserted into the charging circuit between the charging station and the electric vehicle. It is based on a power analyzer that is traced to PTB's national standards and that can also deliver information on the form and the frequency components of electric signals.

The new measuring system thus provides the essential technical foundation for validating the test of fast charging stations with currents of up to 450 A. This is a prerequisite for certified charging stations to meter and bill the quantities of charging energy correctly and reliably despite the great number of influencing factors involved. The measuring system ensures not only smooth charging but also correct energy metering, and it does so without affecting either the data communication between the charging station and the electric vehicle or the electrical power flow.

Sources of support for this development work included the DC Grids European research project that was launched in 2021. This project investigates the factors that affect the measurement trueness of charging stations.

Depending on the technical implementation of the charging station, the new system could be used for tests performed when placing devices on the market and for market surveillance purposes. PTB is accompanying the development of the pertinent regulatory documents in Germany. ▪

Charging an electric vehicle at a fast charging station with the measuring system inserted between the station and the vehicle.

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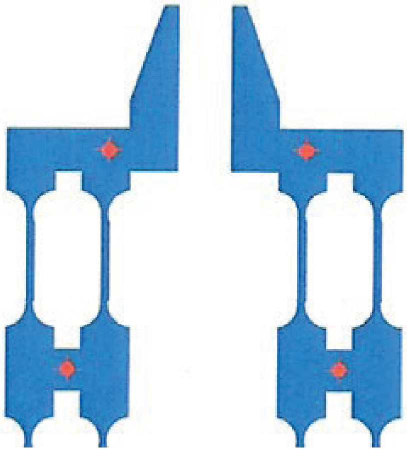
Grip force measurement with optical markers

Especially interesting for
- medical research
- medical cell diagnostics
- the pharmaceutical industry

The ability to measure even the smallest grip forces, in particular for the nondestructive handling and manipulation of highly sensitive materials such as biological cells, is indispensable in medical research and the pharmaceutical industry. PTB came up with a concept that simplifies grip force measurement by optically evaluating markers placed on the gripper jaws. In this way, it is possible to acquire the displacement and position of the grippers and then to calculate the grip force applied. The advantages are that the manufacturing effort is low, the materials can be selected freely, and metal film sensors are not required. The gripper being made of a single material, it protects the analyzed object from chemical impurities. (Technology Offer 437) ▪



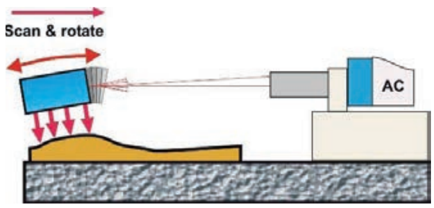
Segmented gripper jaw with markers (red) to measure the grip force

Advantages
- accurate grip force measurement
- optical image assessment
- low manufacturing effort

Measuring free-form surfaces

Especially interesting for
- manufacturers of autocollimators
- the optical industry

A novel procedure for determining surface topographies includes an interferometer as its core element. This interferometer's tilt is detected while it is moved in a special guideway for measuring the surface under test. A large number of measurements performed using this procedure allows the topography of the surface to be determined – in particular of free-form surfaces that exhibit a strong curvature. A mirror element consisting of several partial mirrors considerably enhances the angular measuring range of the tilt for free-form surfaces without decreasing the accuracy of interferometric measurements. (Technology Offer 509) ▪



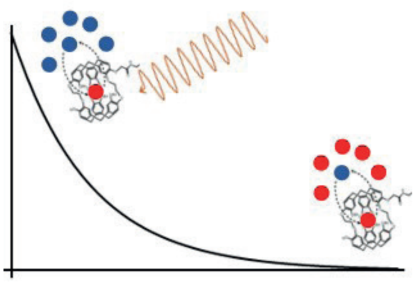
While the interferometer's tilt is measured by means of the autocollimating telescope (ACT), the interferometer determines the topography.

Advantages
- capable of measuring free-form surfaces
- considerably enhanced measuring range
- compatible with conventional autocollimators

Determining biomarkers

Especially interesting for
- biomedical research
- bioanalytics
- medical engineering

In biomedical research and clinical care, it is becoming ever more important to detect biomarkers (pathogenic proteins and cells) quantitatively in order to understand systemic processes or to make decisions as regards diagnostics and therapy. A patent application has been filed for accurate, platform-independent and calibration-free measurement procedures performed on xenon atoms. Developed by PTB, such procedures are an innovative technology for quantifying biomarkers that use xenon-binding antibodies as biosensors. This approach is an alternative to the radioactive or fluorophore markers used to date; it could also prove interesting for vaccine development. (Technology Offers 341 + 535) ▪



Advantages
- high detection sensitivity and accuracy
- calibration-free measurement
- platform-independent results
- use of biosensors

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Presidency handed over

The former President of PTB, Prof. Dr. Joachim Ullrich, passed the baton to Prof. Dr. Cornelia Denz on 1 May 2022. She is the first female president in PTB's more than 135-year history. Before taking on this post, Cornelia Denz headed the Institute of Applied Physics at the Westfälische Wilhelms-Universität Münster for seven years. Because she has been a member of the "Kuratorium" (Advisory Board) for many years, she is already very familiar with PTB. After leading PTB for ten years, Joachim Ullrich will take up a new position as the president of the German Physical Society (DPG).

European metrology partnership

Over the next seven years, the EU will provide 300 million euros in funding for a new metrology research program called the "European Partnership on Metrology". The Member States will contribute at least the same amount. EURAMET e.V. is implementing the program and has already launched a call so that selected projects can start as of mid-2022. As the national metrology institute of Germany, PTB will be significantly involved in most of the research projects. One focus will be on developing metrological solutions in the areas of the Green Deal, digitalization and health, ensuring that the competitiveness of European industry is supported. This also includes a first-class measurement infrastructure.
(Contact: Jörn Stenger, +49 531 592-3000, joern.stenger@ptb.de)

Quantum computer project

The nationwide joint project titled QSolid intends to develop a collaboration platform for a quantum computer based on superconducting circuits within the next five years. It is also planned that a demonstrator system will be set up within this context. For this project, PTB's work will include developing particularly low-noise, next-generation superconducting circuits and methods to improve the control over superconducting qubits. Building on this, calibration services are to be created that can be utilized by industry partners at PTB's Quantum Technology Competence Center. A total of 25 partners are involved in the QSolid project which is being coordinated by Forschungszentrum Jülich. The project budget amounts to 76.3 million euros; 89.8 % of the funding is being provided by the BMBF. (Contact: Lukas Grünhaupt, +49 531 592-9453, lukas.gruenhaupt@ptb.de)

Calidena

An initiative called "Calidena" (a blend of the Spanish words "calidad", quality, and "cadena", chain) is supporting developing countries and countries in transition in improving their quality infrastructure – especially in the agrarian sector – for 18 months. Through its participative approach, this initiative which was launched at PTB brings together producers, buyers, trade chambers, government representatives and QI service providers (metrology, standardization, conformity assessment and accreditation).
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Federal Ministry for Economic Affairs and Climate Action

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 Climate Action.

New research building

The new Walther Meissner Building was officially dedicated at PTB's site in Berlin-Charlottenburg on 22 April 2022. Work will be carried out on quantum and cryosensors, cryo- and primary thermometry and photonic pressure measurements in this research building. One focus is the development, manufacturing and application of PTB's world leading highly sensitive superconducting quantum interference devices (SQUIDs).
(Contact: Frank Melchert, +49 30 3481-7446, frank.melchert@ptb.de)

Awards

Volker Wittstock

Volker Wittstock, a scientist from Department 1.7 *Acoustics and Dynamics*, was named an honorary professor by the Faculty for Mechanical Engineering of the TU Braunschweig in recognition of his many years of commitment as a lecturer on the subject of acoustics.

Lena Ruwe

Lena Ruwe, a researcher in Department 3.7 *Fundamentals of Explosion Protection*, received the Jürgen Warnatz Prize from the German Section of the Combustion Institute (which has its headquarters in Pittsburgh, USA) for her outstanding achievements in the field of combustion and especially for the experimental investigation of combustion processes.

Hayo Zutz

Hayo Zutz, a scientist from Department 6.3 *Radiation Protection Dosimetry*, received the IEC 1906 Award from the International Electrotechnical Commission (IEC) to honor his exceptional contributions to the field of standardization.