PTB’s strontium lattice clock is ticking

Optical transition frequency determined with high accuracy

The frequency of the optical lattice clock, which is based on neutral strontium-87 atoms, has been determined by comparing it to a caesium fountain clock of PTB with a relative uncertainty of $1 \cdot 10^{-15}$. Frequency shifts of the strontium reference transition at 429 THz are under control at a level of better than $2 \cdot 10^{-16}$.

At many metrology and university institutes, optical frequency standards are being intensively developed to be able to realise the base unit “the second” with higher accuracy in future. For this purpose, a group of these experiments uses the electronic transition $^{1}S_{0} - ^{3}P_{0}$ of $^{87}$Sr. Contrary to Cs clocks with their microwave transitions, very narrow absorption lines in the visible spectral range are interrogated in the case of these optical frequency standards, which brings about

Especially interesting for

• high-precision time and frequency measurement
• fundamental physics in space
• metrology institutes
a considerably higher stability. Also the systematic uncertainties are – in some cases – considerably smaller than those of primary Cs clocks.

In optical clocks, either trapped individual ions or clouds of cold neutral atoms are used as absorbers. In the case of lattice clocks with strontium, neutral atoms are trapped in a strong laser field – the optical lattice – for which they have to be cooled down to a few millionths of a kelvin by means of lasers. The movement of the atoms is then reduced to the fraction of an optical wavelength, whereby the Doppler effect becomes negligible. Worldwide, strontium lattice clocks are being developed in at least eight laboratories. Frequency measurements of three experiments are available which show a very good agreement. For the first time now, the frequency of the clock transition of $^{87}$Sr has been measured at PTB in comparison with one of PTB’s Cs fountain clocks. In this frequency measurement, the strontium standard reached a relative uncertainty of below $2 \cdot 10^{-16}$ so that these systematic contributions influence the total uncertainty of $1 \cdot 10^{-15}$ only slightly.

Further optimisations are necessary to reduce the measurement uncertainty still further. This includes controlling the temperature of the black-body radiation of the environment (which influences the clock transition) better than is currently the case, and determining the atomic shift coefficient more exactly. To be able to carry out the respective measurements, the atoms must be transported into a very well controlled environment for the interrogation of the reference transition. A corresponding set-up is currently in the test phase. With this set-up, it will be possible – in clock operation – to reduce the uncertainty of this frequency shift to just a few $10^{-18}$ of the optical frequency. This makes strontium a promising candidate for a re-definition of the second.

Calibration of high-frequency oscilloscopes

Time-domain characterisation of oscilloscopes with a bandwidth of 100 GHz now possible

By means of optoelectronic measurement procedures based on femtosecond laser technology, high-frequency electronics can be reliably calibrated. At PTB, such a non-invasive measurement technology was extended to determine the time response of ultra-fast sampling oscilloscopes having a bandwidth of 100 GHz.

The bandwidth of commercial high-frequency circuits is continuously increasing. For the characterisation of corresponding components, ultra-fast sampling oscilloscopes are used, amongst others, which nowadays have a bandwidth of up to 100 GHz. As the time response of the oscilloscopes distorts the measured signal and as this influence becomes stronger with the frequency, the time response of the oscilloscopes must, for precise high-frequency measurements, be traceably calibrated. Thereby, the applied measurement technology requires a bandwidth which is twice or three times as large as the bandwidth of the oscilloscopes. So far, it has been possible to calibrate oscilloscopes with a bandwidth of 70 GHz at PTB. The set-up – having now been extended – also allows the time response of sampling oscilloscopes with a bandwidth of 100 GHz to be calibrated.

The procedure used for this purpose is based on optoelectronic measurements in the time domain. First of all, ultra-short voltage pulses with a width of less than 2 picoseconds are generated by means of a femtosecond laser in a so-called “photoconductive switch”. The photoconductive switch is integrated in a metallic coplanar waveguide structure on a semiconductor material. The voltage pulses propagate along the waveguide, and their time response can be precisely measured by means of optoelectronic measurement technology. The time axis of the measured waveform is traced back to the SI unit “the second”.

To be able to calibrate instruments with a coaxial input connector by means of these short voltage pulses, the pulses must be transferred from the coplanar to the coaxial waveguide. At PTB, commercial microwave probes are used. After the

Microscope image of the coplanar waveguide structure. The gap in the centre stripline forms the so-called “photoconductive switch” which produces – upon excitation with an ultra-short laser pulse – a picosecond voltage pulse (red waveform) which is propagating along the waveguide structure.
transfer function of the microwave probe has been determined and further experimental influences have been taken into account – also by means of optoelectronic methods – the shape of a voltage pulse entering the oscilloscope can be calculated very precisely. By comparing the entering pulse with the signal measured by the oscilloscope, the pulse response of the oscilloscope can be determined. During the assessment of the measurement results, the uncertainty is determined by means of a Monte Carlo analysis. This allows the oscilloscope to be completely characterised, as it is not only possible to indicate an uncertainty for every point in time of the pulse response, but also because correlations between different points in time are taken into account.

High-precision 3D micrometrology

PTB offers the calibration of ball plates for micro coordinate measuring machines

At novel hemisphere plate standards, measurement uncertainties of less than 0.1 µm can be achieved by combining a special measurement strategy, stable environmental conditions and a very good reproducibility. This considerably improves the testing of micro coordinate measuring machines in industry.

To be able to verify the dimensions of micro components, micro coordinate measuring machines (micro-CMMs) are used in industry which currently achieve length measurement errors of 0.3 µm and less. Testing these micro-CMMs in compliance with international standards must be carried out with suitable measurement standards, e.g. with special ball plates where hemispheres have been wrung to a Zerodur plate. Due to the very low thermal expansion coefficient of the Zerodur glass ceramics, the precisely defined distances are guaranteed, and the special design of the plate, with drill holes in the substrate, makes it possible for the hemispheres to be probed from both sides of the plate. The novel hemisphere plates are calibrated with high precision at PTB by means of a micro-CMM with a tactile sensor.

The systematic deviations of the measuring instrument used can be largely eliminated by means of an error separation technique. Thereby, the hemisphere plate is measured in various orientations to the measuring instrument axes, in an upright and inverse position. The precision of the error separation technique is significantly limited by the reproducibility of the measurements in the various positions. The requirements placed on the stability of the environmental conditions and on the diligence of the operator are thus accordingly high.

A complete calibration comprises repeat measurements in four positions and – in addition – the measurement of parallel gauge blocks in different orientations, in order to determine the length correction of the measurement axes of the micro-CMM. During the measuring time of about 8 hours, the deviations of the micro-CMM to be corrected must be stable to a few nanometers.

The calibration uncertainties attained amount to 50 nm ($k = 2$) for the positions of the hemispheres on the Zerodur plate. Long-term investigations of the procedure showed reproducibilities of better than ± 15 nm for three repeated calibrations on a PTB hemisphere plate.

The measurement results achieved with PTB’s micro-CMM have – within the scope of a bilateral EURAMET project which has just been completed – been compared to the measurement results of the micro-CMM operated at the Swiss metrology institute METAS. Within the range of the estimated measurement uncertainties, a very good agreement hereby resulted.
Special-effect varnishes – looks can be deceiving

New measurement procedures allow a better characterisation of special-effect varnishes

Special-effect varnishes, which are based on interference pigments and exhibit different colours from different perspectives, are growing more and more popular. So far, however, they have been a problem for metrology as both their colour and their saturation and brightness change according to the perspective and the light conditions. To solve this problem, a new robot-based measuring set-up has been established for the characterisation of their visual appearance: With two additional camera systems, it allows an improved metrological assessment of colours, varnishes and coatings.

For industry, it is difficult and time-consuming to guarantee a constant colour quality for special-effect varnishes within the production chain – from the pigment to the varnish and then to the finished product. It is nearly impossible to reproduce existing special-effect varnishes whose exact composition is unknown.

As numerous wavelengths have to be determined for an angular resolved absolute reflection measurement with a defined angle of incidence and of reflection, such measurements have so far taken several hours or even days. A line scan camera at the new robot-based measuring set-up “ARGon3” (3D Appearance Robot-based Goniorefl ectometer) of PTB now reduces the measuring time to just a few minutes, as it can detect a whole spectrum at the same time. It is supplemented by a luminance camera that improves the previous spatial resolution from 20 mm to about 30 µm and thus provides clearly more detailed colour information from a test sample.

The colour coordinates determined here ensure that industrially used colour-measuring instruments are able to provide more precise and comparable data. Thus, the quality control of colours can be improved – both for conventional and for special-effect varnishes.

The size of nanoparticles now traceably determined

PTB measures nanoobjects by means of synchrotron radiation

Dimensional nanometrology is a new field of work at PTB’s laboratory at BESSY II by means of which – for nanolayers – the layer thickness and – for an ensemble of nanoparticles – the mean value and the distribution width of the diameter can be determined. Within the scope of an iMERA-plus project, the diameters in the range of 9 nm to 200 nm of various particles made of gold, silica, ferric oxide, latex and PMMA (acrylic glass) have – for the first time – been traceably measured via small angle X-ray scattering with synchrotron radiation. Thereby, relative uncertainties of 1 % could be achieved.

For some years now, PTB has been using monochromatised synchrotron radiation in the X-ray range to be able to determine the dimensions of nanoobjects. In contrast to X-ray tubes, the wavelength can thereby be optimally adapted to the nanosystem to be examined. To determine the thickness of oxide layers on silicon samples via X-ray reflectometry,
radiation in the range of the oxygen absorption edge at 2.3 nm is used for contrast enhancement, for example, as is the case for the silicon spheres of the Avogadro project.

To determine the diameter of nanoparticles in suspension via small-angle X-ray scattering, wavelengths below 0.5 nm are selected. Such radiation can easily penetrate the thin-walled sample cavity containing the suspension. Thereby, the exact wavelength is measured by means of back reflection of the radiation from a silicon crystal. The scattering angle can be determined by means of length measurements carried out with incremental displacement indicators. The scatter diagram developing in forward direction under small angles – of just a few degrees – is recorded by means of a large-area X-ray detector. For spherical nanoparticles with not too broad a distribution of the diameter, concentric rings result. The radial integration yields an oscillating curve for the scattering intensity as a function of the momentum transfer, to which modelled scattering curves are fitted. From this, not only the mean diameter of the particles is obtained, but also the distribution width, as – contrary to microscopic procedures – the mean is taken via a large number of particles.

If small-angle X-ray scattering is used for surfaces under grazing incidence – as is the case for a number of EMRP projects which are just being launched in the industry call – also nanoparticles or nanostructured surfaces can be characterised.

Better radiation protection at doctor’s surgeries
New facility for the generation of pulsed X-radiation supports the improvement of electronic dosemeters

In the past few years, there has been a change in medicine, industry and research – from continuous X-radiation to pulsed X-radiation. As PTB has discovered, many of the conventional electronic dosemeters therefore do not determine reliable values any more. Thus, in cooperation with the Siemens company, a new facility has been developed which will, for the first time, make the testing of dosemeters for measurements in pulsed radiation fields possible. Worldwide, it is the first facility of its kind.

Especially interesting for
- staff and assisting persons in diagnostic radiology
- manufacturers of area and personal dosemeters

With this facility, all physical parameters of the radiation pulse – tube current and tube voltage, pulse duration and repetition rate – can be adjusted almost independently of each other. Thereby, a special rotating anode X-ray tube is used. The tube current – and thus the ionising radiation – is switched on and off by a grid inside the tube. During that time, the high voltage is applied continuously, which is called “grid-controlled pulsing”. This has made it possible to generate radiation pulses with very short rise and fall times around 50 µs and pulse durations of only 0.2 ms up to continuous operation. The adjustable tube high voltage lies in the range from 40 kV to 125 kV; the tube current can be selected in the range from 0.5 mA to 800 mA. For electrical powers of up to 4 kW, continuous operation is possible; beyond that, only (short-term) pulsed operation is possible. At the maximum possible power of 80 kW, the maximum pulse duration is still 300 ms. The fact that the facility can generate continuous radiation is important for the metrological comparison with the conventional testing facilities and the primary standards of PTB. The pulse repetition rate can be up to 100 Hz.

To make sure that radiation protection can also be guaranteed in pulsed fields of ionising radiation, industry has already started to develop new electronic dosemeters, and PTB is involved in developing the respective standards within IEC and ISO.

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Scientific publication
Monitoring after stroke
A compact, mobile measuring instrument facilitates the monitoring of stroke patients

Stroke is the second most common cause of death in industrial nations and results in serious and long-term disabilities for one third of the survivors. From a diagnostic point of view it would be beneficial to permanently monitor the blood flow of the affected cerebral areas directly after the stroke. A compact, mobile measuring device which has been developed by PTB and cooperation partners can be used directly at the patient's bedside to measure the cerebral perfusion more simply and more frequently.

Four out of five strokes are ischemic infarcts. An artery is constricted and the cerebral perfusion is reduced. In the worst case, cerebral areas will die off. To assess cerebral perfusion at a stroke unit, imaging procedures, e.g. perfusion magnetic resonance imaging or computer tomography, are used. These procedures provide first-class pictures which are used by neurologists and neuroradiologists to decide on suitable therapies. However, the instruments are large, the examinations are expensive and the patients must be taken to special rooms, so that often only few measurements can be made for each patient.

Therefore, PTB together with the Center for Stroke Research Berlin and the Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences in Warsaw have developed a method for the continuous monitoring of cerebral perfusion directly at the patient's bedside. The method is based on a near-infrared reflectometer with a time resolution in the picosecond range. Thus, the individual measurements can be taken comparatively often, e.g. half-hourly, and not only at an interval of several days, as has been the case so far.

For the measurement, short laser pulses with an average power of a few milliwatts are irradiated into the head of the patient by means of optical fibres via a special cap. The optical contrast agent indocyanine green (ICG) is applied intravenously as a bolus. The contrast agent bolus modifies the optical properties of the illuminated tissue and, subsequently, the reflect ed light pulses. The data analysis exploits the high time resolution of the instrument and is, therefore, especially sensitive to cortical changes. In addition, events on the diseased and on the healthy hemisphere are compared with each other. In this way, information on the bolus migration at the cortex – and therefore on the cerebral perfusion – can be derived.

The method was successfully tested at the Department of Neurology of the Charité with several patients suffering from an acute unilateral ischemic stroke. For this purpose, a functional model of the PTB measuring device, which was certified by a notified body according to the Medical Devices Act, was used. There is hope that the positive results achieved by the stroke units can be further improved due to the quasi-continuous monitoring of the cerebral perfusion of stroke patients.
Laser radiation with less coherence

Especially interesting for
• manufacturers of optical microscopes

The use of lasers as a light source for imaging systems has great advantages – e.g. due to the exactly known wavelength – but also one disadvantage: owing to the spatial coherence of the laser beams, so-called “speckle artefacts” occur. Conventional procedures for the reduction of the coherence are not suited for pulsed laser radiation with a low repetition rate and a great coherence length. Thanks to an invention of PTB, speckle suppression is possible. It mainly consists of a new fibre coupling method and can be used in different optical microscopes in which lasers or super LEDs are used as light sources. The technology can be realised with extremely little technical and economic effort, and is also suited for non-imaging systems.

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Licence partner wanted

Sleeve reduces risk of explosion

Especially interesting for
• the chemical and pharmaceutical industry
• saw mills and furniture factories

Instead of T8 fluorescent lamps, so-called T5 fluorescent lamps are used increas-ingly by industry today, as they are more energy-efficient and – thus – more economical. They have, however, the disadvantage of heating up more and more – and more irregularly – due to fatigue. Due to these “hotspots”, they can be used in explosion-hazardous areas only to a very limited extent. A newly developed sleeve now distributes the developing heat so that other ignition-physical conditions develop. T5 fluorescent lamps up to 54 W HO which are provided with these sleeves can also be used economically in explosion-hazardous areas.

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Licence partner wanted

Homogeneous MR images

Especially interesting for
• developers of MR technology
• hospitals

Magnetic Resonance Imaging (MRI) at high magnetic fields up to 7 tesla allows a better image resolution, shorter measuring times and – thus – better diagnostics. A disadvantage is that, in the case of higher magnetic fields, the images are illuminated only inhomogeneously due to wave phenomena. With multi-channel transmit-receive coil systems it is, however, possible to avoid these image artefacts, but interferences due to mutual couplings between the elements of a multi-channel coil system complicate the precise compensation of signal voids in the MR image. This disturbing cross talk is effectively suppressed by means of a PTB invention. In the transmit and receive mode, it implements the electric current-controlled operation of each individual coil element so that the individual coil elements can be driven independently of each other. This decoupling scheme offers, first of all, an improvement of the existing high-field MR technology, but it could also lead to the development of novel applications such as, e.g., implantable MR coils. The instrument – for which EU and US patents have been granted – is a joint development of PTB and the University of Leipzig.

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MR image of a cylindrical water phantom (central axial slice). Above: One coil element is active; the others lead to severe inhomogeneities due to coupling effects (yellow). Below: By using this invention, the field distribution becomes more homogeneous.

Contact person for questions about technology transfer
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### Awards

**Call for the Helmholtz Prize 2012**

The Helmholtz Prize, endowed with 20,000 €, is the most distinguished German award in the world of metrology and is awarded every two years for outstanding scientific and technological research work in the field of "Precision Measurement in Physics, Chemistry and Medicine."

The submitted work must have been developed in Europe or in cooperation with scientists working in Germany and must represent an original performance which has been completed only recently. The work to be submitted must be a recent research achievement of a theoretical or experimental nature, either contributing to fundamentals or aiming at concrete applications.

The application deadline is 30 September 2011.

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**Fritz Riehle**

The Head of Division 4 Optics received the IFCS I.I. Rabi Award "for outstanding contributions to the field of atomic frequency standards, including pioneering research and development of optical frequency standards and their measurement" at this year's IFCS / EFTF meeting in San Francisco.

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### Dates

- **24-25.6.2011** International Workshop 2nd Annual Symposium of the Berlin Ultrahigh Field Facility
  - Location: MDC Berlin Buch, Communications Center. Contact: Bernd Ittermann. Phone +49 (0)30 3481-7318

- **27.6.-1.7.2011** International Single Photon Workshop 2011 (SPW 2011)
  - Location: Braunschweig, Hotel Mercure. Contact: Stefan Kück. Phone +49 (0)531 592-4500

- **18-21.7.2011** WE Heraeus Seminar "Astrophysics, Clocks and Fundamental Constants"
  - Location: Bad Honnef, Physikzentrum. Contact: Ekkehard Peik. Phone +49 (0)531 592-4400

- **12-14.9.2011** 10th IMEKO Symposium Laser Metrology for Precision Measurement and Inspection in Industry (LMPMI)
  - Location: PTB Braunschweig. Contact: Harald Bosse. Phone +49 (0)531 592-5010

  - Special concerts focusing on time. Location: PTB Braunschweig. Contact: Christine Haubold. Phone +49 (0)531 592-3007

- **4-6.10.2011** 37th Annual Meeting of the German Society of Color Science and Application (DfWg)
  - Location: PTB Braunschweig, Conference Centre. Contact: Andreas Höpe. Phone +49 (0)531 592-4520

- **5-6.10.2011** Meeting of the Technical Committee Pressure and Vacuum
  - Location: PTB Berlin, Lecture Hall. Contact: Karl Jousten. Phone +49 (0)30 3481-7262

- **5-7.10.2011** DEGA Academy Building Acoustics: Basic Principles and Applications
  - Location: PTB Braunschweig, Vieweg Building. Contacts: Werner Scholl, Marion Witwer. Phone +49 (0)531 592-1700, +49 (0)531 592-1701

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### Publications

**maßstäbe Issue no. 11 “Kraft messen” (Measuring Force)**

The popular-science magazine of PTB

**PTB-Mitteilungen Issue 1/2011**

Focus: Physical and chemical safety engineering and explosion protection

For further information and to obtain copies:

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