PTBnews

Metrology
Technology
Services
Cooperation

03.2

High-accuracy optical frequency standard

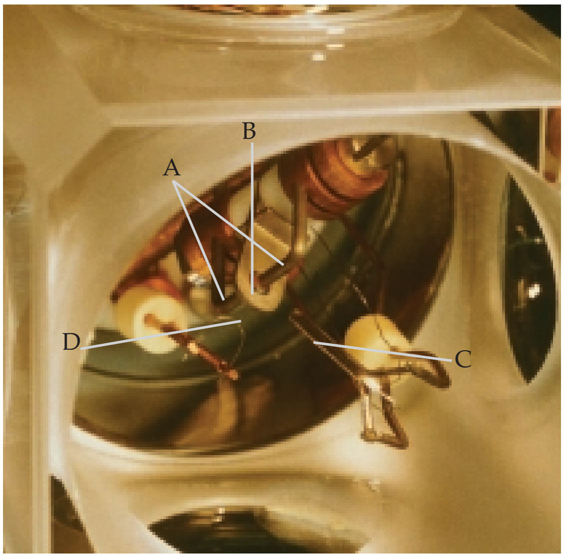
With the aid of a single stored ytterbium ion, the frequency of blue laser light has been stabilized with an accuracy of a few hertz. Thus, a reference frequency in the optical wavelength region has been established which, at present, is among the most accurate in the world.

The SI units for time (second) and frequency (hertz) are the measurement units which can be realized by far with the highest precision of any SI unit. Today, PTB and other metrology institutes operate the most precise cesium atomic clocks in the world on a routine basis. With these clocks a relative accuracy of almost 10^{-15} is achieved for the realization of timing signals and standard frequencies (see PTB-news 01.3). However, precision measurements of fundamental constants as well as new tests of fundamental physical theories require the comparison of precise clocks and call for atomic frequency standards of even higher accuracy and short-time stability. This can be achieved by increasing the frequency of the clock signal with which the reference atoms are excited. In this context the shift from the microwave range (cesium clock: 9,2 GHz) to the higher optical frequency region (100 THz to 1000 THz) is of particular advantage. The accuracy of an optical frequency standard can be transferred to the microwave range and to any other optical frequency using optical frequency comb generators (see PTB-news 00.3).

A single laser-cooled ion stored in a radiofrequency ion trap offers a particularly high accuracy potential for optical frequency standards. The $^{171}Yb^{+}$ ion investigated at PTB is one of the ions for which systematic perturbations of the atomic transition frequency seem to be controllable up to a relative uncertainty of 10^{-18}. In the experiments the resonance signal of a stored $^{171}Yb^{+}$ ion was used to stabilize the frequency of a specially designed 435,5 nm semiconductor laser system. The laser frequency thus defined in atomic terms was measured using a frequency comb generator and the PTB cesium reference standard CSF1. The statistical uncertainty component dominates the 1-σ-uncertainty of 6 Hz which was achieved so far for the measured frequency value (688 358 979 309 312 Hz) so far achieved. The frequency values measured within several weeks differ by only ± 2,6 Hz.

Very likely the uncertainty of the $^{171}Yb^{+}$ frequency standard can be further reduced by several orders of magnitude in future work.

At present an experiment is being prepared to directly compare two $^{171}Yb^{+}$ standards. The goal is to obtain information about the influence of the storage conditions on the atomic transition frequency – independent of the accuracy and stability limitations of the cesium reference. Future work will aim at significantly reducing the measurement uncertainty.



The ion trap used in the experiment: A) end cap electrodes and B) ring electrode (1,3 mm diameter) to generate the quadrupole trap field, C) ytterbium oven, D) electron source (heatable filament)

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National traceability network for chemical analytics

Not only are chemical analyses extremely numerous and manifold but they also are significant for society and commerce. To provide these measurements with a joint and reliable framework, the PTB has set up a traceability system for chemical analytics, together with the BAM (Bundesanstalt für Materialforschung und -prüfung, Federal Institute for Materials Testing and Research), the UBA (Umweltbundesamt, Federal Environment Office) and the DGKC (Deutsche Gesellschaft für klinische Chemie, German Society for Clinical Chemistry). This national network increasingly ensures the traceability of the measurement results to the International System of units (SI), thus adding to their credibility and acceptance, preventing expensive multiple measurements in many areas (such as medicine) and improving the prerequisites for unhindered worldwide trade and economic competition.

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National traceability network for chemical analytics

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In chemical analytics, an increasing number of customers, accreditation centres and authorities therefore require the statement of measurement uncertainties and that the measurement results being traceable to acknowledged reference points. This is also reflected by the application of the worldwide accepted standard ISO/IEC 17025 "General Requirements for Calibration and Test Laboratories." In chemistry a metrological traceability system is already available in partial areas, e.g. in clinical chemistry, in certain fields of electrochemistry (pH-value, electrolytic conductivity) and in gas analysis. For elemental analytics, such a traceability system is at present being set up. Laboratories at the working level are provided with the calibration means necessary for traceability via an intermediate level (e.g.: chemical calibration laboratories accredited within the Deutscher Kalibrierdienst (DKD, German Calibration Service)) or directly from national reference institutes (e.g. in the form of certified reference materials).

In chemistry the existing structures up to now can cover the becessary traceability chains only in part, so the traceability system is being further extended. The network is used to bundle the scattered technical competence available in the area of chemical analysis. The PTB as the institute entrusted by law with the realization, maintenance and dissemination of the units has a managing function here. Within the network, the tasks are distributed among the partners according to their competence and capacities. All partners participate on their own behalf in international key comparisons organized under an agreement between the national metrology institutes. Apart from the gain in efficiency, this structure allows a fast and practice-based estimate of the metrological needs which are continuously discussed with the users. A national network for metrology in chemistry is a new approach to coping with the numerous tasks in chemistry. The strategic approach in Germany has, therefore, raised worldwide interest.

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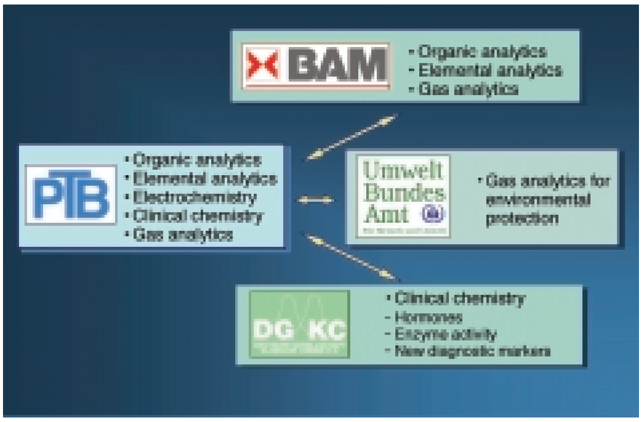

The partners in the national network intended to ensure the metrological traceability of chemical measurements in Germany. The arrows illustrate contractual relations between the individual partners.

Measurement of ultrashort oscilloscope risetimes

The intrinsic oscilloscope risetime must be known for correct interpretation of oscilloscope measurements. For this purpose PTB has developed an optoelectronic method to determine the risetime of 50 GHz oscilloscopes. The method utilizes optical femtosecond pulses and allows traceable measurements of oscilloscope risetimes of only a few picoseconds.

Broad-band 50 GHz oscilloscopes are indispensable tools in the development of ultrafast electronic circuits in data processing and communication technology. These oscilloscopes have very short intrinsic risetimes and allow the visualization of ultrafast electric signals. Nonetheless, the risetime is not zero, and the measurement curves may be distorted. To correct this distortion, the user needs to know the risetime of the oscilloscope. As its determination calls for a measurement method with an even higher temporal resolution, methods of femtosecond optics are used.

To determine the risetime of 50 GHz oscilloscopes, short voltage pulses of approx. 1 ps are generated on a coplanar waveguide by short-circuiting a photoconductive switch with laser pulses of 100 fs. The voltage pulses are coupled into the oscilloscope via a microwave probing tip. An opto-electronic probing method allows one to measure the voltage pulses on the waveguide with a temporal resolution of 300 fs. By means of such measurements it is possible to determine the deformation of the pulses on their way to the oscilloscope and to calculate their shape at the oscilloscope input. Deconvolution of the oscilloscope curve with the known input pulses gives the response characteristics of the oscilloscope, in particular, its risetime.

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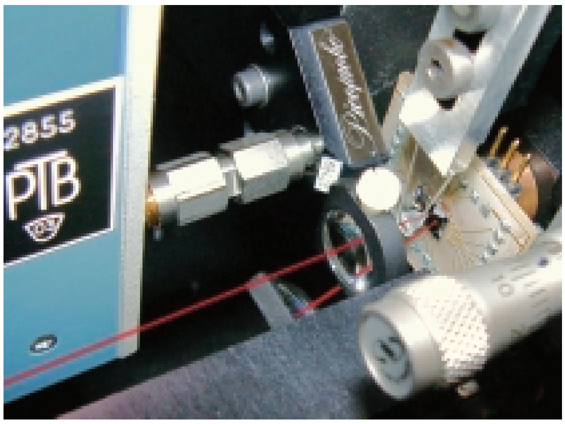

Photoconductive switch and laser beams (coloured in red) for the generation and measurement of ultrashort voltage pulses.

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Measurement of ultrashort oscilloscope risetimes
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First measurements on a 50 GHz oscilloscope yielded risetimes in the range of 7 ps with a typical expanded measurement uncertainty of 1,5 ps.

Oscilloscopes calibrated by this method allow for reliable measurements in the area of microwave electronics.

International Awards for Andreas Bauch and Ekkehard Peik

At this year's IEEE Frequency Control Symposium, held together with the European Frequency and Time Forum in Tampa, Fl., USA, Dr. Andreas Bauch and Dr. Ekkehard Peik, both of PTB Time and Frequency Section, were awarded prizes for their outstanding scientific achievements.

Dr. Andreas Bauch received the I. I. Rabi Award of the IEEE "in recognition of outstanding contributions to the development, evaluation and operation of primary frequency standards".

Dr. Ekkehard Peik received the "Prix Jeune Chercheur" of the Société Chronométrique de France "considering his achievements in several fields of frequency standards development."

Our very best congratulations!

Redefinition of the temperature unit?

The present definition of the kelvin links the unit of temperature with a material property. It would be more consistent to determine the value of the Boltzmann constant, *k*, instead. For this purpose, *k* must first be determined with distinctly lower uncertainty than presently possible. PTB seeks to achieve this objective through improved dielectric constant gas thermometry.

The temperature of the triple point of water is presently determined to be 273,16 K by definition. Thus, the unit kelvin is linked to a material property which is rather arbitrary. Instead, it would be advantageous to proceed in the same way as with other units: to relate the unit to a fundamental constant and fix the value of this constant. By this no temperature value (and no measurement method) would be favoured. For the kelvin, the corresponding constant is the Boltzmann constant, k, because temperature always appears as "thermal energy" kT in fundamental laws of physics. For example, according to present knowledge one might think of redefining the kelvin as the change of temperature that results in a change of the internal energy of 20 709 755 J for an ideal gas of 10^{30} point particles without internal degrees of freedom.

To ensure that such a redefinition would maintain the relative uncertainty of about $3 \cdot 10^{-7}$ currently achieved for the realization of the temperature unit, the Boltzmann constant must be known with similar accuracy. At present, however, its relative uncertainty is still about $2 \cdot 10^{-6}$. First of all, therefore, this uncertainty must be reduced considerably.

In principle the Boltzmann constant can be determined with any primary thermometer by measuring kT at a known temperature (ideally at the triple point of water). The present value of k has been determined at NIST by acoustic gas thermometry measuring the velocity of sound in a gas. A study recently completed by PTB shows that another variant of gas thermometry, dielectric constant gas thermometry with helium, offers good chances of further reducing the uncertainty as required – in particular, because the polarizability of the helium atom can now be calculated very precisely by quantum-mechanics. This measurement method determines the temperature- and pressure-dependent dielectric constant of helium from the change in capacitance occurring when the gas is pumped out of a helium-filled capacitor. For many years now PTB has successfully applied dielectric constant gas thermometry in the low-temperature range. PTB has therefore set itself the goal of further improving dielectric constant gas thermometry. The relative standard uncertainty which can be achieved today in determining the Boltzmann constant will be reduced from $15 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$ in a first step and by another order of magnitude in a second step.

This project, which will certainly take a decade, has now been tackled, with first investigations carried out on a gas thermometer system recently installed. Spectral radiation measurements on the basis of Planck's radiation formula will support the project and help confirm the results.

Ludwig Boltzmann, 1844-1906

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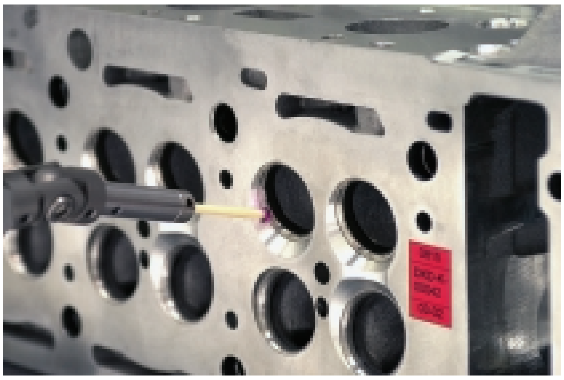
Virtual CMM in use in industry

The “virtual coordinate measuring machine”, developed by PTB, is ready for practical use. A whole network of calibration laboratories will employ the new procedure and make it available to industry. With this procedure, realistic measurement uncertainties for coordinate measurements can now be determined automatically.

Coordinate measuring machines (CMM) as universal measuring facilities are widely used for quality assurance in industry where they serve to measure motor units and many other workpieces. To determine the suitability of a CMM for a measurement task and to define reasonable product tolerances – a significant requirement from an economic point of view in particular –, it is important to know the measurement uncertainty for the features of a workpiece.

These measurement uncertainties can be determined by the virtual CMM. The procedure is based on measurements simulating the metrological behaviour of the CMM. The software module needed for this purpose can now be obtained from two German CMM manufacturers. It is directly integrated into the CMM software and together with the measurement report it automatically furnishes the measurement uncertainty assigned to the measurement result.

In a joint project with partners from industry and universities, the procedure has been confirmed on the basis of more than 13 000 comparison measurements so that the “Deutscher Kalibrierdienst” (DKD, German Calibration Services) could accredit several laboratories for the use of this procedure. Thus a network of calibration laboratories is available capable to calibrate any prismatic workpieces as reference standards. These calibrated standards can be supplied to industry enabling it to ensure the traceability of its measuring facilities.



Calibration of a cylinder head as a reference standard

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PTB time service prolonged

In the future radio alarm and station clocks as well as many other time services will continue to receive legal time from PTB via the DCF77 transmitter located near Frankfurt. The contract with Telekom affiliate T-Systems MediaBroadcast has been renewed and extended until the end of 2013.

Long waves are practically not hindered by obstacles. They can be received inside buildings by means of small antennae and relatively simple circuits. Therefore, even in the age of GPS, long-wave emission of time signals is still very attractive. In addition, the PTB time service excels by virtue of its reliability and availability. In the contract now renewed, T-Systems guarantees PTB, as under the previous contract, unrestricted use of the long-wave transmitter DCF77 in Mainflingen near Frankfurt for 99,7 percent of the year. In 2002, nearly 99,95 percent usage was achieved. At the transmitter the time information is coded as a data stream and transmitted with a power of approx. 30 kW by means of three atomic clocks and a complex electronic control and monitoring system. Thus PTB supplies legal time for the whole of Germany as an infrastructural service of the State. The signal provides station clocks, traffic light systems, switch clocks in power distribution systems, private radio clocks, broadcasting and television companies and many other users with the exact time.

The other possibilities of using the DCF77 transmitter also remain unaltered by the new contract. Apart from the transmission of the time information, the additional modulation of the carrier phase of the DCF77 transmitter is used for high precision applications. Furthermore, the carrier frequency, 77,5 kHz, is derived from the atomic clocks in Mainflingen so that the relative deviation of the carrier frequency from the nominal value averaged over one day is below $1 \cdot 10^{-12}$. Permanent comparisons with the primary atomic clocks in Braunschweig, which are among the most precise clocks in the world, ensure the correctness of the signals emitted.

PTB time signals – emitted by the DCF77 long-wave transmitter – can be received by normal radio clocks within a radius of approx. 2000 km.

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