

Progress Report on Electrical Metrology at the PTB between 2013 and 2015 on the Occasion of the 29th Meeting of the CCEM

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1. Electrical Quantum Standards

1.1 Josephson voltage standards

Fabrication of binary-divided arrays of overdamped SNS Josephson junctions with $\text{Nb}_x\text{Si}_{1-x}$ barriers for AC applications is well established at PTB (S: superconductor, N: normal metal). The 10-V series arrays contain about 70,000 junctions designed for operation at a microwave frequency of 70 GHz. Using double-stacked Josephson junctions, series arrays delivering 20 V were successfully fabricated and characterized. (Johannes.Kohlmann@ptb.de)

The development of Josephson impedance bridges has progressed from the previously reported 1/1 ratios for resistance and capacitance (10 k Ω / 10 k Ω and 100 pF / 100 pF) to ratios different from unity. Using 10-V binary-divided Josephson arrays the uncertainty of 100 pF to 10 pF ratio measurements could be reduced to a few parts in 10^8 between 100 Hz and 5 kHz. At power line frequencies, the uncertainty was 3 parts in 10^7 . (Luis.Palafox@ptb.de)

PTB has developed an AC quantum voltmeter for industry within the framework of a technology transfer project with an instrument developer and a calibration laboratory. The AC quantum voltmeter is based on a 10-V programmable Josephson array and provides DC and AC calibrations up to the kHz range for industry-common equipment. The set-up has demonstrated excellent uncertainty when it is used as conventional DC Josephson voltage standard (2 parts in 10^{10} ($k = 2$)). It is also well suited for measurements in the low-frequency AC range where the uncertainty is better than $1.7 \mu\text{V}/\text{V}^{-1}$ ($k = 2$) at 1 kHz. The new AC quantum voltmeter is a practical and robust system that suits the needs of the general metrology industry. In a follow-up project the partners started working on an extension of the set-up towards an AC quantum calibrator. This work is supported by the German Federal Ministry of Economics and Technology. (Jinni.Lee@ptb.de, Ralf.Behr@ptb.de)

The development of pulse-driven Josephson junction series arrays has been continued, focusing on arrays with up to 9,000 SNS Josephson junctions with $\text{Nb}_x\text{Si}_{1-x}$ barriers embedded in the centre conductor of a coplanar waveguide transmission line. The integration of this large number of junctions per array was achieved by using triple-stacked junctions. A standard window process ensures a very high fabrication yield. By operating two arrays on one chip connected in series, output voltages of 355 mV_{RMS} (1 V_{PP}) were achieved. The measurement set-up was improved by using an 8-channel pulse pattern generator (PPG) to operate 8 arrays (on 4 chips) in series with a total number of 63,000 junctions. Output voltages of 1 V_{RMS} (2.8 V_{PP}) were successfully synthesized with a signal-to-noise ratio better than 120 dBc. Due to the large code-memory and a new feature (pulse repetition function) of the PPG the frequency range of the system was increased (10 Hz to 1 MHz). It was successfully demonstrated that the pulse-driven Josephson arrays could be operated in a pulse-tube cryocooler. Stable operation margins were determined in a temperature range from 4.2 K up to 5.6 K. (Oliver.Kieler@ptb.de, Johannes.Kohlmann@ptb.de)

1.2 Single-electron transport

In a proof of principle experiment the functionality of a self-referenced quantized current source was demonstrated at low pumping frequency. The device consisted of three GaAs single-electron pumps (SEP) connected in series and two metallic single-electron detectors situated between two adjacent pumps. The single-electron detectors allowed the in-situ detection of individual failure events of the SEP and thus an order of magnitude improvement of the SEP current uncertainty. (Frank.Hohls@ptb.de)

In the existing self-referenced quantized current sources conventional single-electron transistors (SETs) are used as detectors of pumping failure events. These SETs have a typical bandwidth of up to 1 kHz, which limits the achievable error-corrected current. Therefore, PTB started the development of so-called RF SET detectors, allowing for a substantially higher bandwidth (MHz) with nearly the same sensitivity for charge detection. The successful integration of such detectors based on Al SETs into GaAs pump circuits should enable a self-referenced quantized current source with at least 10 pA output current. (Ralf.Dolata@ptb.de)

An ultrastable low-noise current amplifier (ULCA) for the measurement of small currents was developed with particular focus on the study of single-electron quantized current sources. The instrument is capable of measuring and sourcing currents from the pA range up to 5 nA. A low current noise of 2.4 fA/ $\sqrt{\text{Hz}}$ helps to keep measurement times short. The transfer coefficient is highly stable versus time, temperature, and current amplitude. A cryogenic current comparator is used for calibration, providing traceability to the quantum Hall effect. Within one week after calibration, the uncertainty contribution from short-term fluctuations and drift of the transfer coefficient is about 0.1 parts per million (ppm). The long-term drift is typically 5 ppm/yr. (Hansjoerg.Scherer@ptb.de, Dietmar.Drung@ptb.de)

1.3 Quantum Hall effect

PTB has established the epitaxial growth of graphene by the thermal decomposition of SiC. Growth studies showed that Ar pretreatment could have a positive influence on the growth of epitaxial graphene monolayers on SiC. The graphene layers were suitable for high-precision quantum Hall metrology. (Klaus.Pierz@ptb.de)

A quantum Hall resistance measured at AC constitutes a quantum impedance standard for the realisation of the capacitance unit, the farad, without need for a conventional capacitance artefact and with an even smaller uncertainty. The potential of graphene for this application was explored in the frame of the European Metrology Research Programme (EMRP) project GraphOhm (SIB51). The first AC measurements showed very promising results: at frequencies in the kHz range the $i = 2$ plateau is found to be perfectly flat, in contrast to plateaus of conventional GaAs devices. The frequency dependence is of similar size as in GaAs, and was found to depend on the layout design of the graphene device. This opens a route for further improvement, eliminating the need for special shielding as required for GaAs devices. (Juergen.Schurr@ptb.de)

2. Voltage, Resistance, Current, and Impedance

A compact n/8 inductive voltage divider (IVD) was developed for the frequency range between 1 kHz and 100 kHz and voltages up to 5 V. The specified division ratio was chosen in the first development step to meet the requirements of two-channel instrumentation amplifiers with binary (6 dB) amplification levels. The desired frequency and uncertainty range required a two-stage IVD design with coaxial windings. Additionally, inductive components for the IVD bootstrapping calibration were developed such as a supply transformer, a calibration transformer, and a detection transformer. These components form the calibration set-up which was realized with a triaxial differential branch and voltage controlled shields to minimize capacitive stray currents. The IVD calibration yielded in-phase

and quadrature corrections within 6 ppm and 1 ppm, respectively, both with ($k=2$) uncertainties below 1 ppm at 100 kHz. (Florian.Beug@ptb.de)

So far, AC current sensing resistors (AC shunts) have mainly been calibrated at technical frequencies from 16 $\frac{2}{3}$ Hz to 1 kHz. A recalculation of the measurement uncertainties for AC-DC current transfer resulted in an extension of the calibration capabilities including now currents from 1 mA to 100 A at frequencies from 10 Hz to 100 kHz with measurement uncertainties between 5 $\mu\Omega/\Omega$ and 500 $\mu\Omega/\Omega$. (Torsten.Funck@ptb.de)

PTB plans to extend its calibration service for DC electrical conductivity to cover semiconducting materials in addition to metallic ones, for which CMC entries have already been established. A measurement set-up for samples up to 5 by 5 cm² is in operation and initial measurements of silicon samples with a conductivity of 14 S/m showed good reproducibility. The set-up was also used to measure square-shaped metallic samples that are used as reference standards for eddy current conductivity meters. (Bernd.Schumacher@ptb.de)

3. AC/DC Transfer

The AC-DC transfer differences occurring in planar thermal converters at low frequencies were determined using an asynchronous sampling method. To calculate the rms value of the measured signal from the sampling data, a sine-fit was applied and the transfer differences between 5 Hz and 45 Hz were determined with an expanded uncertainty of 1.2×10^{-6} . A comparison with measurements obtained with the conventional method, which uses different heater power levels, showed an excellent agreement with E_N -values of 0.2 to 0.7. This verifies the assumption that the AC-DC transfer difference of the investigated thermal converter is proportional to the heating power at low frequencies. (Torsten.Funck@ptb.de)

4. Power and Energy

PTB has maintained the voltage ratio error and phase displacement of voltage transformers with several standard voltage transformers (SVTs) for many years. In order to validate the existing measurement capabilities and to extend the measurement range to higher voltages, a new step-up method was investigated using capacitive voltage dividers (CVDs), which serve as transfer standards. Several auxiliary standards have been built up for the step-up procedure, such as a low-voltage capacitor box with selectable capacitances between 1 nF to 300 nF and a two-stage buffer amplifier with accuracy in the order of 10^{-7} . With this method, the first two SVTs (6 kV and 35 kV type) were calibrated with uncertainties around 3×10^{-6} and 5×10^{-6} , respectively. These newly determined errors match with the historical data of the last 50 years within their respective uncertainties. The extension to higher-rated voltages up to 800 kV / $\sqrt{3}$ is planned for the years 2015 and 2016 using a recently ordered SVT. (Enrico.Mohns@ptb.de)

A prototype of a damped-capacitive high-voltage divider for impulse voltages up to 1000 kV was designed and constructed. The aim of this work is to set up a new standard divider for lightning (1.2/50 μ s) and switching (250/2500 μ s) impulse voltages in the high and ultra-high voltage regime. So far traceability for these quantities is generally available only up to 500 kV. First results indicate an improvement of the uncertainty of the amplitude and time parameters on the present values of PTB, which are 1% for the front time as well as the time to half value and 0.5 % for the peak value. A complete measuring system including the divider and an accurate shielded transient recorder with adaptive probes will be constructed. Due to the modular design of the new prototype, the divider is easy-to-transport and is extendable to 1500 kV with the aid of an additional 500 kV module. (Johann.Meisner@ptb.de)

5. Magnetic Measurements

The maintenance of the unit of the magnetic flux density, Tesla, using nuclear magnetic resonance (NMR) methods could be significantly improved with respect to the long-term stability. The measurement uncertainties could be reduced by a factor of 5 with a newly developed dynamic earth field compensation system using PTB's tri-axial Braunbek coil system controlled by software. The system has been successfully employed in the comparison of earth-level DC magnetic flux density P1-APMP.EM-S14. (Hans.Harcken@ptb.de)

Inductive measurements of precessional magnetization dynamics have been used to characterize magnetic tunnel junction (MTJ) systems as used for spin torque magnetic memories or magnetic sensor devices. It has been shown that inductive measurements allow non-destructive wafer scale metrology of key MTJ material parameters such as the critical spin torque current density. (Sibylle.Sievers@ptb.de)

Metrology for magneto-thermo electrical effects of magnetic thin films and nanostructures has been developed. This allowed first measurements of the thermo-electrical signature of a single magnetic domain wall inside a magnetic nanowire. (Hans.W.Schumacher@ptb.de)

6. High Frequency and Fields

6.1 Electromagnetic fields, antenna measurement techniques

PTB has made progress towards precise on-site electromagnetic field measurements employing unmanned aerial vehicles (UAVs). These octocopters are stable airborne platforms for signal-in-space measurements with extended observation period compared to a conventional aircraft. A ground-based reference station provides improved localization information for the on-board receiver unit. This system reduces the position error during repeated flight patterns. Automatic start, flight along predefined GPS/EGNOS waypoints and automatic landing make such UAVs simple to use. We have designed an on-board receiver system for synchronous sampling of 3D-measurement data and position in space and have started its evaluation on PTB's open area test site. (Thorsten.Schrader@ptb.de)

Within a project funded by the German Federal Office for Radiation Protection, a new exposure set-up for cell cultures was designed based on a TEM cell. Dosimetry for the exposition of human blood cells with modern communication signals such as LTE, UMTS, and GSM exploiting a vector signal generator was established. In cooperation with the University of Würzburg, immortalized and primary blood cells were exposed with different specific absorption rates. The end points include cell function, differentiation, DNA repair, cell cycle, genotoxicity, epigenetics, and apoptosis and are evaluated for three independent replica. Results are expected in 2016. (Thomas.Kleine-Ostmann@ptb.de)

6.2 High-frequency measurement techniques

A thermoelectric waveguide power sensor has been developed that is suitable as transfer standard for the R900 waveguide band (75 GHz to 110 GHz). Due to its excellent performance it will replace waveguide thermistors that have been used as transfer standards so far. Equivalent thermoelectric sensors for the R620 and R400 waveguide band are currently under development. Traceable measurements of scattering parameters in rectangular waveguides were established up to 110 GHz. The key comparison on RF power (CCEM.RF-K25.W, 33-50 GHz), piloted by PTB, was successfully completed (Rolf.Judaschke@ptb.de).

PTB has developed a wideband dielectric loss tangent measurement method based on on-wafer coplanar waveguide measurements, which extends the measurement range of existing transmission-line techniques by a factor of ten. For typical microwave substrates such as GaAs, alumina, and quartz,

loss tangents on the order of 10^{-4} were successfully extracted for frequencies between 10 and 125 GHz and independently verified with split-cylinder resonator measurements. (Uwe.Arz@ptb.de)

In a cooperation between NIST, PTB, and a German research institute, crosstalk corrections for coplanar-waveguide scattering-parameter calibrations in the mm- and sub-mm-wave frequency range were developed. While the crosstalk corrections can improve measurement accuracy, the effectiveness of the corrections depends on a number of factors, including the length of the access lines, transverse dimensions, the separation between the crosstalk standards, and the substrate configuration. (Uwe.Arz@ptb.de)

Optoelectronic techniques based on femtosecond lasers are well suited for the characterization of high-frequency electric devices. At PTB such optoelectronic techniques have been used to develop a broadband time-domain vector network analyzer which can be applied to measurements on coplanar waveguides. The bandwidth of this device exceeds 500 GHz with a frequency spacing of 500 MHz. The optoelectronic vector network analyzer allows for the characterization of fast sampling oscilloscopes, photodetectors, and electric pulse generators. (Mark.Bieler@ptb.de)

A low-reflectivity optoelectronic sensor for the detection of continuous wave GHz and THz radiation has been constructed. The sensor utilizes nonlinear optoelectronic techniques and has been calibrated with the help of a calibrated THz radiometer, thus allowing for quantitative electric field measurements. This has been demonstrated by measuring the spatially resolved emission pattern of a 100 GHz standard gain horn antenna. (Mark.Bieler@ptb.de)