Progress Report on Electrical Metrology at the PTB between 2015 and 2017 on the Occasion of the 30th Meeting of the CCEM

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1. Electrical Quantum Standards

1.1 Josephson voltage standards

The development of pulse-driven Josephson junction series arrays has been continued with the goal of increasing the output voltage of a single array. To this end, the number of junctions in a single array has been increased from 9,000 to 14,000 SNS Josephson junctions with Nb_xSi_{1-x} barriers embedded in the centre conductor of a coplanar waveguide transmission line. The integration of this large number of junctions was achieved by using fourfold-stacked junctions. An optimized standard window process ensures a very high fabrication yield. By operating two arrays on one chip connected in series, output voltages above 400 mV_{RMS} (above 1.1 V_{PP}) were achieved. The measurement set-up was further improved including high-quality chip carrier systems for mounting of, and connection to the arrays. Using an 8-channel pulse pattern generator to operate 8 arrays (on 4 chips) in series with a total number of 93,000 junctions, output voltages of 1.5 V_{RMS} have been synthesized with a signal-to-noise ratio better than 125 dBc. (Oliver.Kieler@ptb.de, Johannes.Kohlmann@ptb.de)

A two-terminal-pair impedance bridge based on pulse-driven Josephson arrays was used to link a 10 nF capacitance standard to the quantised Hall resistance at an amplitude of 20 mV_{rms} at 1233 Hz. Uncertainties caused by contact resistances in a two-terminal-pair definition were avoided by a triple-series connection of the quantum Hall resistance. The capacitance agrees within 1.3 parts in 10^8 with that obtained from a transformer-based ratio bridge. Sources of systematic uncertainties were investigated and the combined relative uncertainty for the link of the 10 nF capacitance standard was determined to be 13.9 nF/F (k =1). The combined relative uncertainty of the bridge itself is below 1×10^{-8} (k = 1). (Stephan.Bauer@ptb.de)

The Josephson impedance bridge based on binary-divided arrays has progressed to a semi-automated calibration tool able to perform a frequency sweep from 25 Hz to 10 kHz in less than two hours. It has been used for comparisons with newly developed impedance bridges from SP and LNE. An analysis of systematic errors has been performed, which focused on the measurement of capacitance standards. The unavoidable transients of binary-divided Josephson arrays have been identified as a major source of uncertainty. A detailed uncertainty budget showed uncertainties from 0.9×10^{-8} to 81.1×10^{-8} for 1:1 and 1:10 ratio measurements with 10 pF and 100 pF capacitors. (Luis.Palafox@ptb.de)

The AC quantum voltmeter was advanced to an AC quantum calibrator by combining it with a set of traceable standard resistors. The software framework was extended to calibrate resistors, voltage and current sources in DC and AC mode using a potentiometric method. Resistance measurements at DC and from 10 Hz up to 2 kHz agreed with the results of conventional calibration methods, with uncertainties lower than 10^{-6} in the range from 1 Ω to 100 kΩ. For current, the range between 3 µA and 1 A was covered with only four standard resistors. (Martin.Bauer@ptb.de, Ralf.Behr@ptb.de)

In cooperation with PTB's thermometry department a two-channel pseudo-random Josephson voltage noise source is under development for use in a practical quantum voltage based Johnson noise thermometer for the temperature range 273 K to 1000 K. While in the final version only one voltage noise channel is required, the two-channel approach will be used in the development phase to reliably assess the type B uncertainty contributions of the analog and digital electronics of the thermometer. (Franz.Ahlers@ptb.de)

1.2 Single-electron transport

Systematic studies of the fabrication process led to an improved reproducibility of GaAs single-electron pumps with sub-ppm uncertainty. Furthermore, the sensitivity of single-electron detectors was improved. The implementation of RF reflectometry for fast frequency-multiplexed readout of multiple single-electron detectors enabled the parallel detection of single-electron events with bandwidth in the 10 kHz range at very high (6 sigma) signal-to-noise ratio. The successful integration of charge detectors and reflectometry readout in an array of single-electron pumps was used for on-chip validation of electron transfer probabilities with single-electron precision. (Niels.Ubbelohde@ptb.de)

The standard version of the ultrastable low-noise current amplifier (ULCA) was commercialized and the calibration of the ULCA transresistance by means of a cryogenic current comparator is offered by PTB. Calibrations of small-current ammeters (electrometers) and sources with the ULCA were demonstrated, and the advantages in comparison with alternative calibration methods were confirmed. Several new ULCA versions with special features for different applications were developed and characterized. (Hansjoerg.Scherer@ptb.de, Dietmar.Drung@ptb.de)

In order to further explore the performance of GaAs single-electron pumps, a standard ULCA was used to measure their output current of the order of 100 pA. These measurements demonstrated agreement between the measured current and the predicted value within a record low total uncertainty of 0.16 µA/A. (Frank.Hohls@ptb.de, Hansjoerg.Scherer@ptb.de)

A new concept of the Josephson traveling-wave parametric amplifier was developed to improve electrical measurements at the quantum limit. The concept exploits the quadratic nonlinearity of a serial array of RF-SQUIDs embedded in a superconducting transmission line. It allows operation in the favorable three-wave-mixing mode with minimal phase mismatch and offers simultaneously large bandwidth, high gain, and potentially quantum-limited noise performance. Prototype circuits were fabricated in Niobium technology and a gain of about 13 dB was achieved at 6 GHz. (Ralf.Dolata@ptb.de)

1.3 Quantum Hall effect

For quantum Hall metrology with graphene, PTB developed an improved sublimation growth technique, which yielded large and ultra-smooth graphene monolayers on SiC substrates. The homogenous graphene growth is achieved by nucleation of additional carbon supplied by thermal decomposition of a polymer. A European patent was granted for this method. Measurements of the quantum Hall resistance (QHR) demonstrated the superior quality of the graphene monolayers. (Klaus.Pierz@ptb.de)

The magnetocapacitance and the associated dissipation factor of epitaxial graphene Hall bars have been investigated and used to model the frequency dependence of graphene-based QHR devices. The double-shielding technique developed with GaAs-based QHR devices has been successfully applied to a graphene device. The agreement between AC-QHR in Graphene and GaAs was confirmed with an uncertainty of 2.5 x 10^{-9}. (Juergen.Schurr@ptb.de)

2. Voltage, Resistance, Current, AC/DC Transfer, and Impedance

Due to the development of AC-DC current shunts towards lower measurement uncertainties, the requirement has arisen to determine their non-decade DC resistance value with higher precision. For currents above 1 A, this measurement can no longer be performed with conventional resistance bridges. For this purpose, a new method is developed that allows calibrations to be performed with an expanded uncertainty of less than 1 x 10^{-6}. (Bernd.Schumacher@ptb.de)

The calibration of bridge standards was improved by a newly developed measuring set-up. The new set-up allows bridge standards to be calibrated in a frequency range from 225 Hz to 5 kHz with significantly improved signal stability and reduced calibration effort. Compared to the previously used calibration set-up, the new set-up provides equally small uncertainties for high-precision measurements at 225 Hz and more stable calibration conditions with reduced uncertainty at high measuring frequencies up to 5 kHz. (Florian.Beug@ptb.de)

There is an increasing demand for the calibration of AC currents below 1 mA at frequencies up to at least 100 kHz. Since the sensitivity of thermal converters is not sufficient at these low current levels, the use of amplifiers is indispensable. Newly designed AC-DC transfer standards augmenting a thermal converter with an amplifier and a shunt work well down to less than 100 µA at frequencies up to 1 MHz with transfer differences of less than 400 µA/A. (Torsten.Funck@ptb.de)

The Supplementary Comparison EURAMET.EM-S31 (capacitance and capacitance ratio) has been successfully completed and the final report will be published soon. (Juergen.Schurr@ptb.de)

3. Power and Energy

Power losses of components for reactive power compensation in electrical grids like reactors or capacitors considerably reduce the efficiency of power transmission. Therefore, manufacturers of such components are interested in measuring these losses during the production process with traceable and calibrated loss measuring systems. For this purpose, a calibration system for power losses has been developed at PTB based on the sampling of voltage and current. The voltage and current range of the measurement system is limited by the standard voltage transformer and standard current transformer in use and the phantom power source which emulates the reactive power of reactors or capacitors with adjustable losses. The highest reactive power that can be emulated is 300 MVAr and corresponds to the maximum test voltage and current of 150 kV and 2 kA, respectively, at 50 Hz. The uncertainty of the standard is below 50×10^{-6}. (Enrico.Mohns@ptb.de)

Together with VSL and CENAM, PTB has prepared the key comparison for electrical power at line frequencies, CCEM-K5 2017. In total 11 NMIs will partipate in the CCEM-K5 2017. Two digital power transfer standards of the same type will be used as reference standards. In order to characterize the instruments, PTB has performed preliminary measurements at voltages of 120 V and 240 V, a current of 5 A, and power factors between 0 lead and 0 lag at the reference frequency of 53 Hz. Due to critical results for one of the standards the planned start of the comparison in February 2017 had to be slightly postponed. At the time of writing, the envisioned start date is March 2017. (Matthias.Schmidt@ptb.de)

4. Magnetic Measurements

The sensitivity of inductive measurements of precessional magnetization dynamics was significantly improved by an interferometric technique, which suppresses background signal contributions. The broadband vector network analyser ferromagnetic resonance setup can be used for the characterization of anisotropy in individual magnetic microstructures. (Sibylle.Sievers@ptb.de)

The previously developed metrology for magneto-thermo electrical effects of magnetic thin films and nanostructures has been applied to the detection of the position of magnetic domain walls in magnetic nanowires with perpendicular magnetic anisotropy. The detection scheme is based on the anomalous Nernst effect. It allows the domain wall position to be detected with a resolution below 20 nm in metallic and semiconducting systems and enables future studies of domain wall propagation dynamics in spintronic materials. (Hans.W.Schumacher@ptb.de)

The EMPIR *NanoMag*, Project 15SIB06, was launched in September 2016. It will provide tools and methods for measurements of magnetic fields with micro or nano-scale spatial resolution traceable to macroscopic SI standards. Different stray field measurement tools, namely magnetic force microscopy, magnetooptical indicator film imaging, and scanning Hall and scanning magneto resistive field measurements, are advanced and compared. Calibration artefacts suitable for traceable on-site calibrations are developed. Initiated by *NanoMag*, the IEC TC113 "Nanotechnology standardisation for electrical and electronic products and systems" established a Preliminary Work Item to develop technical specifications for a standard on "Spatially resolved local magnetic field measurements on the micrometre and nanometre scale". (Hans.W.Schumacher@ptb.de)

5. High Frequency and Fields

5.1 Electromagnetic fields, antenna measurement techniques

Using its antenna scanner PTB has made progress in the development of traceable calibrations of a wide range of different antenna types. As the free-space antenna gain or factor is related to the position of the phase center, robust techniques to determine the frequency dependent phase center position were needed. A method based on regression analysis of an angle dependent phase measurement was implemented. Using the Theil-Sen estimator gave best results. Furthermore, the role of multi-path effects in antenna calibration was investigated. It turned out that errors due to multi-path propagation could be corrected applying a virtual endfire antenna array to a series of different antenna measurement distances. Creating a Dolph-Tschebbycheff-Array with sufficiently high group factor allowed transmission measurements to be corrected to remove the systematic errors of multi-path propagation in an anechoic room with limited size and performance of the absorbers. (Thomas.Kleine-Ostmann@ptb.de)

PTB has further improved its capabilities of precise on-site electromagnetic field measurements employing unmanned aerial systems (UAS). A commercial octocopter is used, which was improved by shielding, precision localization (real-time kinematics), and an FPGA based sampling unit. The high-frequency measuring system stores synchronously time, location and a band-limited sampling data set. Data evaluation can be done offline without loss of information. All internal clock signals and frequencies are coherently derived from a reference oscillator onboard. As first application of the UAS, signals of terrestrial navigation and radar installations were measured in order to investigate the possible influence of wind power plants on those services. (Thorsten.Schrader@ptb.de)

5.2 High-frequency measurement techniques

A novel R900 calorimeter has been developed for the calibration of thermoelectric and thermistor waveguide transfer power standards. It is based on dielectric feeding waveguides resulting in improved measurement dynamic range and higher long-term stability. Based on the previously developed R900 thermoelectric transfer standard, high performance thermoelectric standards have been developed and successfully tested in the R620 waveguide band (50 GHz to 75 GHz). In 2017, PTB will extend its power calibration capabilities up to 170 GHz by the development of both R1400 waveguide calorimeter and thermoelectric transfer standards. (Rolf.Judaschke@ptb.de)

PTB has extended its measurement capabilities for scattering parameters to 67 GHz in the coaxial connector system PC1.85mm. For all other connector types, calibration service is now offered for scattering parameters in the entire complex plane for both reflection and transmission measurements. (Rolf.Judaschke@ptb.de)

A high-frequency device consisting of coplanar and coaxial elements has been characterized using on-wafer vector network analysis in the frequency domain and a recently developed laser-based vector network analyzer in the time domain. The comparison of both methods from 10 GHz to 110 GHz showed good agreement in almost the entire frequency range. These results can be taken as a first encouraging step towards mutual verification of time- and frequency-domain high-frequency device characterization. (Uwe.Arz@ptb.de, Mark.Bieler@ptb.de)

Within the European Metrology Programme for Innovation and Research (EMPIR), PTB coordinates the joint research project ”Microwave measurements for planar circuits and components” (PlanarCal), which has started successfully. PlanarCal aims at the development of traceable planar S-parameter metrology and the extension of the applicability of on-wafer microwave measurements both to higher frequencies and to nanodevices. (Uwe.Arz@ptb.de)

Optoelectronic techniques based on femtosecond lasers have been used to develop a broadband time-domain vector network analyzer which can be applied to measurements on coplanar waveguides. The device has been used for the characterization of a high-speed balanced photoreceiver. A comparison with measurements using commercially available instrumentation done at NPL shows a good agreement between the different measuring techniques. (Mark.Bieler@ptb.de)