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Mutual validation of PTB's Josephson and INRIM-POLITO's electronic impedance bridges for the realization of the farad from graphene quantum standards

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Abstract – In the International System of Units, the impedance units can be realized from the quantum Hall effect, a macroscopic quantum phenomenon producing quantized resistance values. Established experiments employ individual GaAs devices [1], but novel materials such as graphene can be exploited to realize the units with relaxed experimental conditions. Furthermore, simple traceability chains can be implemented with novel digital impedance bridges. By combining novel digital impedance bridges and graphene quantum standards, an easy-to-operate and affordable impedance standard has been developed in the framework of the European EMPIR project 18SIB07 GIQS (Graphene Impedance Quantum Standards). An onsite comparison of an electronic and a Josephson impedance bridge developed at INRIM (Istituto Nazionale di Ricerca Metrologica, Italy) together with POLITO (Politecnico di Torino, Italy) and at PTB (Physikalisch-Technische Bundesanstalt, Germany), respectively, were organized for their mutual validation in the realization of the farad from graphene quantum standards. The result of the comparison and the last progresses of the GIQS project are here presented.

I. INTRODUCTION

In the International System of Units (SI), a possible realization of the unit of electrical capacitance can be obtained directly from the quantized Hall resistance (QHR) $R_H = R_K/i$, where $R_K = h/e^2 = 25\,812.807\,459\,304\,5\,\Omega$ is the exactly defined von Klitzing constant [2]. The resistance R_H depends only on the Planck constant h , the elementary charge e and by the small integer i . The traditionally employed GaAs/AlGaAs QHR devices require extreme experimental conditions, as very high magnetic field (of about 10 T) and very low temperatures (of about 1 K), to show the QHR $R_H = 12\,906.403\,729\,652\,25\,\Omega$, corresponding to $i = 2$ and typically exploited for metrological applica-

tions.

In the AC regime, the farad can be obtained from the QHR by means of suitable impedance bridges. With the traditional transformer-ratio impedance bridges this was only possible implementing the quadrature bridge, which is a double product impedance bridge [3] comparing two resistors and two capacitors at a properly chosen fixed angular frequency. The implementation of the quadrature bridge principle [4] is a very complex electrical network with many electromagnetic components. Digitally-assisted implementations [5] reduce the network complexity to some extent and allow a partial automation. With two resistances calibrated against a QHR standard or that are QHR standards themselves, measured in the AC regime (ACQHR standards), the quadrature bridge can be used to realize the farad from the QHR. To date, only one laboratory worldwide operates a permanent quadrature bridge with two quantum Hall effect devices in a single cryostat [1], a massive and complex experiment filling an entire laboratory.

A valid alternative to quadrature bridges to directly realize the farad from the QHR can be digital impedance bridges, which allow the comparison of impedances with arbitrary phase angles. This is possible with recently developed impedance bridges based on adjustable digital signal synthesizers that provide much more flexibility with respect to older analog generators. These bridges can compare a single resistance standard and a single capacitance standard. The digital approach allows the design and implementation of much simpler bridges [6, 7]. A further alternative can be a special type of digital impedance bridge, which exploits two pulse-driven Josephson junction arrays (also called Josephson Arbitrary Waveform Synthesizer, JAWS) to provide arbitrary voltage ratios with an arbitrary phase angle. By providing quantum based AC signals with high accuracy and extremely low harmonic content [8], the JAWS can efficiently be adopted for impedance metrol-

ogy [9].

The aim of the European EMPIR project 18SIB07 GIQS [10] is to enable an economically efficient traceability of impedance quantities to the defining constants of the SI that can be adopted by national metrology institutes, calibration centers and industry. In this project, graphene QHR devices were adopted for the realization of electrical units. This because they display the quantum Hall effect at lower magnetic field (e.g., at 5 T) and higher temperature (e.g., at 4.2 K) than those of the well-established GaAs devices [11], allowing relaxed operating conditions achievable with simpler and less expensive cryogenic systems. Graphene QHR standards can be thus exploited as affordable and easy-to-operate impedance standards that can be perfectly combined with all types of impedance bridges.

In this framework, an electronic and a Josephson impedance bridge were developed by INRIM [12], together with POLITO, and by PTB [13], respectively. An onsite comparison of the bridges was organized for their mutual validation and to assess their performance in the realization of the farad. The INRIM-POLITO's travelling electronic impedance bridge was moved to PTB to perform measurements with both bridges on the same graphene ACQHR standard, developed at PTB. The developed digital impedance bridges and their comparison are described in sections II and III, respectively. The results are discussed in section IV.

II. DIGITAL IMPEDANCE BRIDGES

A digital impedance bridge is a measuring system operating in the AC regime that allows to determine an impedance ratio by the ratio of two signals generated by an adjustable digital signal source. Figure 1 shows the principle schematic of a four-terminal-pair digital impedance bridge. In a four-terminal-pair digital impedance bridge the impedances Z_1 and Z_2 are four-terminal-pair impedances defined as $Z_k^{4TP} = V_{HPk}/I_{LCk}$, where V_{HPk} is the voltage at the high potential terminal-pair of the k th impedance and I_{LCk} is the current at the low current terminal-pair of the k th impedance, with the boundary conditions $I_{HPk} = 0$, $V_{LPk} = 0$ and $I_{LPk} = 0$, where I_{HPk} and I_{LPk} are the currents at the high and low potential terminal-pair of the k th impedance, and V_{LPk} is the voltage at its low potential terminal-pair. The four-terminal-pair definition of the impedances is obtained by means of auxiliary circuits (I_1 , I_2 and E_L in Figure 1). When the bridge is balanced, that is, when the reading of the detector D is zero at the same time at all the detection points (dashed lines in Figure 1), the equation $W = Z_1/Z_2 = -E_1/E_2$ holds. Both the INRIM's and PTB's impedance bridges are four-terminal-pair digital impedance bridges.

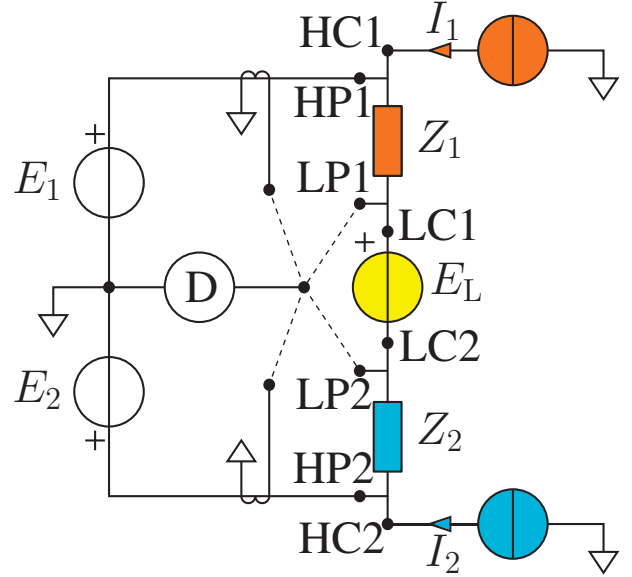


Fig. 1. Principle schematic (only inner conductors) of a four-terminal-pair digital impedance bridge.

A. INRIM-POLITO's electronic impedance bridge

The INRIM-POLITO's electronic impedance bridge [12] is a four-terminal-pair impedance bridge that determines an impedance ratio by the voltage ratio generated by an electronic polyphase generator. With an auxiliary injection added to the schematic of Figure 1, the uncertainty is minimized when the impedance magnitude ratio $|W| = 1$. The bridge is thus optimized for the direct comparison of a standard capacitor with an ACQHR standard when the nominal value of the standard capacitor and the frequency are chosen to obtain the 1 : 1 ratio condition. The bridge is based on a 7-channel polyphase digital sine wave generator developed by the University of Zielona Góra, Poland: two channels produce the reference voltage ratio against which the impedance ratio is compared; three other channels drive the auxiliary circuits realizing the four terminal-pair impedance definition; and a further channel is the auxiliary injection. The bridge balance is detected by a phase-sensitive detector and the bridge balance procedure is automated. The bridge balancing time is about 20 min. The target uncertainty of the bridge is at the level of 10^{-7} or less.

B. PTB's Josephson impedance bridge

The PTB's Josephson impedance bridge [13] is a four-terminal-pair impedance bridge that determines an impedance ratio by the voltage ratio generated by two JAWS [8]. Two independent arrays are operated in liquid helium. The required rf pulses are generated with a pulse pattern generator with two independent memories sharing the same clock. The phase angle is set by shifting the

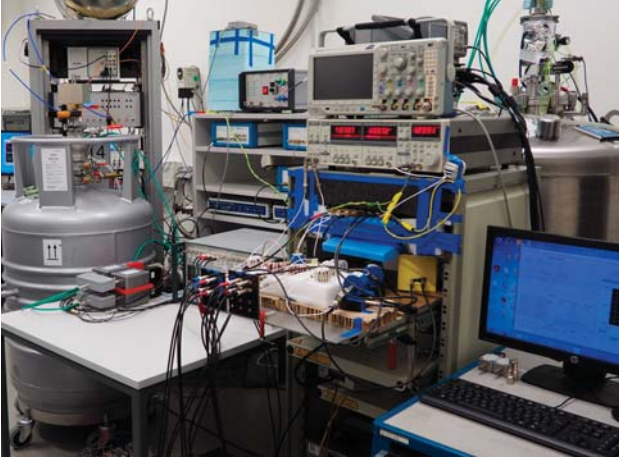


Fig. 2. Implementation of the INRIM-POLITO's (right) and PTB's (left) impedance bridges at PTB. The cryogenic systems hosting the graphene ACQHR and the JAWS device are shown on the right and left of the picture, respectively.

start bit of the pulse pattern in the second memory with respect to that in the first memory. In the PTB's Josephson impedance bridge, the ratio between the waveforms synthesized by the JAWS at arbitrary frequencies is equal to the ratio between the impedances under comparison when the bridge is balanced. The target uncertainty of the bridge is at the level of parts in 10^{-8} or less.

III. COMPARISON OF THE DIGITAL IMPEDANCE BRIDGES

The mutual validation of the PTB's Josephson and the INRIM-POLITO's electronic impedance bridge was performed by moving the INRIM-POLITO's bridge to PTB and reassembling it in the laboratory of PTB's bridge, as shown in Figure 2, where also the cryogenic systems hosting the graphene ACQHR and the JAWS device are located.

The temperature controlled calibrated impedance standards employed in the technical assessment of the bridges are a $12.9\text{ k}\Omega$ resistance standard and a 10 nF capacitance standard. Both the standards have small time-dependent drifts, a few $\text{n}\Omega/\Omega$ per day and a few nF/F per day, respectively, which do not need to be considered for the comparison since the measurements of the same standards are typically performed with both the impedance bridges within one working day. All standards are located in the same two-stage thermostat with a stability in the mK range.

The graphene ACQHR device employed in the comparison is a graphene device fabricated in the cleanroom facility of the PTB as described in the literature [14]. The number of contacts is minimized to 6 to reduce the stray capacitances by allowing at the same time the required triple series connection [15]. The holder of the device

was specifically designed for AC measurements with two electrodes above and below the device splitted in its center in two parts [16], the high-side and low-side shields, thus allowing the double-shield technique [17]. In the following study, this technique is not implemented: the high-side shields are kept floating, while the low-side shields are shorted to the low potential side of the device. The ACQHR device was preliminary characterized in both the DC and AC regimes, and resulted to be well quantized at a magnetic flux density of 5 T at a temperature of 4.2 K . In these conditions, the graphene ACQHR device was measured with both bridges against the temperature-controlled impedance standards.

The combined uncertainties are estimated separately for each bridge. For the INRIM-POLITO's electronic impedance bridge, the main uncertainty sources are:

- Bridge reading.
- Phase error of the auxiliary injection.
- Crosstalk between the channels of the generator.
- Cable correction in the measurements involving the ACQHR device (this component is zero for temperature-controlled impedances).
- Asymmetry error due to a not perfect equalization of the currents.

For the PTB's Josephson impedance bridge, the main uncertainty sources are:

- Bridge reading.
- Crosstalk between the Josephson arrays and the inductance of the arrays.
- Cable corrections.
- Bridge deviation error from an improper balance of currents in the high potential arms.

The bridges were assessed by performing the triangle measurements shown in Figure 3 at the working frequency $f = 1233.15\text{ Hz}$ with both bridges and comparing the results. The $C_1 = 10\text{ nF}$ capacitance standard was first calibrated directly against the graphene ACQHR standard R_{QHR} and then against the $R_1 = 12.9\text{ k}\Omega$ resistance standard in turn calibrated against the graphene ACQHR standard R_{QHR} . For each bridge, the result of the triangle measurement is thus the comparison between the results obtained with the two calibrations of the capacitance standard, given by $(R_{\text{QHR}}/R_1)(R_1 C_2)/(R_{\text{QHR}} C_2) - 1$, and evaluate the self-consistency of each bridge.

The results of the triangle measurements with the PTB's Josephson and the INRIM-POLITO's electronic impedance bridges are 0.036 ± 0.032 and 0.024 ± 0.388 ,

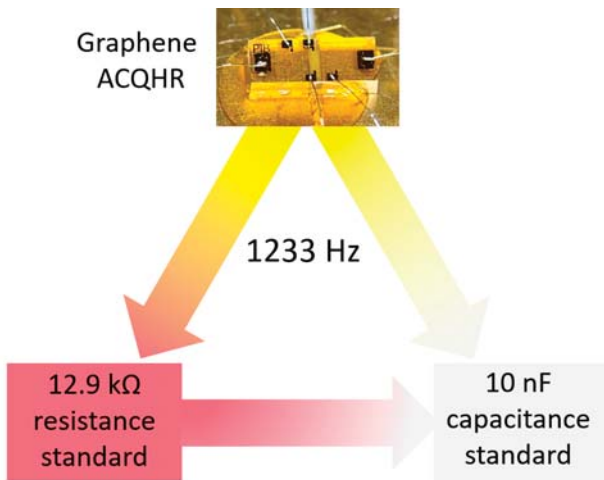


Fig. 3. Schematic of the triangle measurements performed in the technical assessment of the INRIM-POLITO's and PTB's bridges at 1233 Hz. At top of the picture there is a photo of the graphene ACQHR device fabricated by PTB.

respectively. The mutual validation of the bridges was then obtained from the discrepancies between the calibrations of the standards obtained with the two bridges, that is, 0.012 ± 0.390 . All the reported uncertainties are combined uncertainties with a coverage factor $k = 2$. The measurements are thus compatible within the expanded uncertainties ($k = 2$).

IV. DISCUSSION

Thanks to the onsite comparison between the INRIM-POLITO's and PTB's impedance bridges it was possible to exchange our knowledge and experiences, and thus solve some issues that affected the bridges. For example, the behaviour of the digital source employed in the INRIM-POLITO's bridge was dependent on the room temperature, which was not controlled, and was also affected by the switches involved in the balance automatization. The current equalization in the circuit was also improved. Finally, the comparison of the bridges resulted in a very good agreement of a few parts in 10^8 within the expanded uncertainty. The Josephson impedance bridge has indeed an uncertainty that is lower than that of the electronic bridge, and is able to operate over a wide range of impedance ratios and frequencies. The electronic impedance bridge is an affordable impedance bridge able to calibrate like and quadrature impedance standards, including ACQHR standards, in the 1 : 1 magnitude ratio with an uncertainty of about one part in 10^7 ($k = 1$), suitable for primary impedance metrology.

More details about the results and the methods adopted in the comparison will be presented at the conference.

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