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# Realization of the farad from the quantum Hall effect with a fully digital bridge: progress report

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**Summary.** — In the revised International System of Units (SI), the unit of electrical capacitance, the farad, is defined from the exact value of the von Klitzing constant,  $R_K = h/e^2 = 25\,812.807\,459\,304\,5\,\Omega$ , and from the unit of time. This opens the possibility of realizing the farad directly from the quantum Hall effect by means of suitable impedance bridges. We present here the design, the implementation and a preliminary validation against the Italian national capacitance scale of a four-terminal-pair fully-digital impedance bridge optimized for the direct comparison of an 8 nF standard capacitor with a quantum Hall resistance standard at a frequency of about 1541 Hz, where the impedance magnitude ratio is 1 : 1. The uncertainty of the 1 : 1 comparison, according to a preliminary evaluation, is at the level of  $10^{-7}$ . We also present here a possible new traceability chain for the farad based on a fully-digital impedance bridge and on a graphene quantized Hall resistance in the AC regime.

## 1. – Introduction

Since 20 May 2019, the definition of the electrical units in the International System of Units (SI) [1] is based on two fundamental constants with exactly specified quantity values [2]: the elementary charge  $e = 1.602\,176\,634 \times 10^{-19}$  C and the Planck's constant  $h = 6.626\,070\,15 \times 10^{-34}$  J s. As a consequence, the unit of electrical resistance ohm ( $\Omega$ ) can be realized by means of quantized Hall resistance (QHR) standards [1, Appendix 2], being the von Klitzing constant  $R_K = h/e^2 = 25\,812.807\,459\,304\,5\,\Omega$ .

The units of electrical capacitance and inductance, farad (F) and henry (H), linked to the ohm by the unit of time, can be realized by means of quantum Hall impedance (ACQHR) standards [3] with impedance bridges operating at frequencies in the kilohertz range. Traditionally, the farad is realized from the QHR through several resistance and impedance comparisons by means of transformer-ratio coaxial bridges [4]. These traditional bridges are complex networks of electromagnetic devices requiring laborious balance procedures manually performed by trained personnel.

Digitally-assisted bridges, where the adjustable electromagnetic devices are replaced by signal generators based on digital-to-analogue converters (DACs), can partially automate the operation [5].

The current Italian traceability chain of the farad, which is at the Istituto Nazionale di Ricerca Metrologica (INRIM), is based on digitally-assisted bridges [6] and on a calculable AC-DC transfer resistance, in turn calibrated against the QHR in the DC regime.

Fully-digital impedance bridges allow a simple, compact and fully automated realization of the farad directly from the ACQHR [7, 8]. Transformers or calibrated electromagnetic devices are no longer required, such that the accuracy of these bridges depends only on the properties of the digital signal generators.

National Metrology Institutes (NMIs) usually realize the QHR with GaAs/AlGaAs heterostructures, requiring high magnetic flux density ( $\approx 10$  T) and very low temperature ( $\approx 1$  K). Graphene devices are a promising alternative for metrological applications, since they need lower magnetic flux density and higher temperature [9].

This work presents a plan to develop a new traceability chain for the farad, according to the SI. A fully-digital impedance bridge is employed to calibrate a  $C = 8$  nF capacitor directly against a QHR with nominal value  $R_H = R_K/2 \approx 12\,906.4\,\Omega$  at the frequency  $f = 1541$  Hz. With these parameters,  $2\pi f R_H C \approx 1$ , such that the bridge operates in the 1 : 1 ratio configuration. The target uncertainty is of about  $10^{-7}$ , which is adequate to maintain the national standard and to disseminate the capacitance scale.

## 2. – New traceability chain

Figure 1 shows the diagram of the traceability chain for the realization of the farad from the ACQHR based on a fully-digital impedance bridge. An 8 nF gas-dielectric capacitor is calibrated against an ACQHR by means of a fully-digital impedance bridge, described in the next section. The calibration is performed at frequency  $f \approx 1541$  Hz, such that the ratio between the impedance of the capacitance standard and that of the

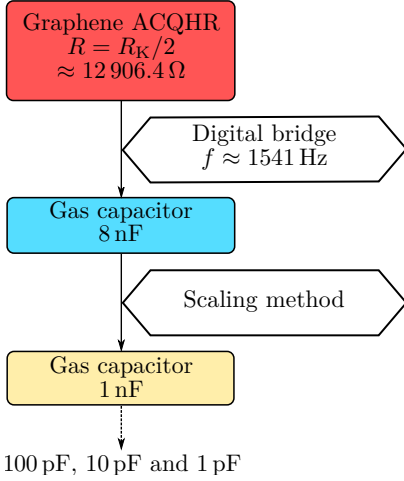


Fig. 1. – Diagram of the traceability chain for the realization of the farad from the ACQHR based on a fully-digital impedance bridge.

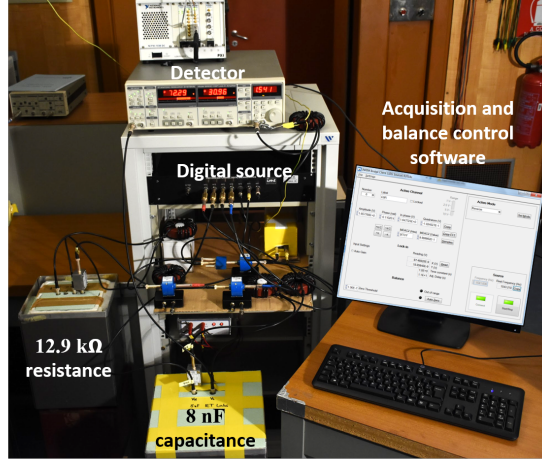


Fig. 2. – Photograph of the four-terminal-pair fully-digital impedance bridge implemented at INRIM. The bridge is currently composed of a digital signal generator, a detector, a  $12\,906.4\ \Omega$  resistance standard and an  $8\ \text{nF}$  capacitance standard. The bridge balance is controlled by a custom software.

ACQHR is unitary. This condition minimizes the bridge uncertainty.

The  $8\ \text{nF}$  gas capacitor is then employed to calibrate a  $1\ \text{nF}$  capacitance standard which is then scaled to other decadal values.

### 3. – Four-terminal-pair fully-digital impedance bridge

The implementation of the four-terminal-pair fully-digital impedance bridge, shown in fig. 2, is based on a digital signal generator able to control the signals in both amplitude and phase. The bridge can thus compare impedances of different type. The topology of the bridge herewith described is optimized for unit impedance ratios.

The digital signal generator<sup>(1)</sup> drives seven independent output channels. Two channels generate the voltage ratio against which the impedance ratio is compared. Three channels generate the signals for the realization of the four-terminal-pair definition of the impedances. One further channel generates an auxiliary injection to improve the bridge accuracy in the  $1 : 1$  ratio configuration. The last channel generates the reference signal for the detector.

The digital signal generator and the detector are controlled by a custom software so

<sup>(1)</sup> The digital signal generator is developed by the University of Zielona Góra [10], Poland, in the framework of the European project EMRP SIB53 AIM QuTE, *automated impedance metrology extending the quantum toolbox for electricity* [8].

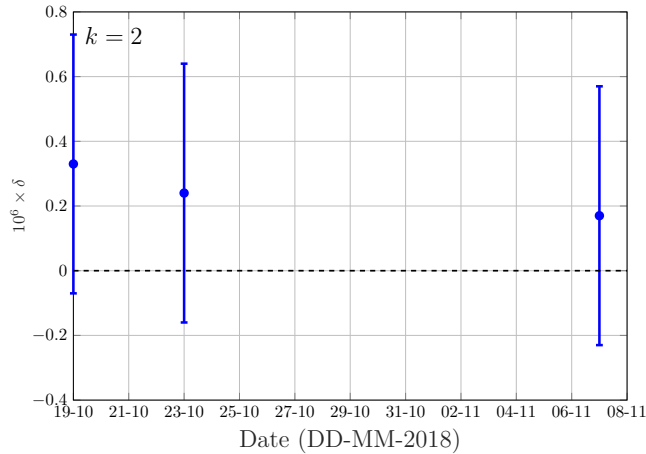


Fig. 3. – Summary plot of the final results  $\delta$  of three comparisons.  $\delta$  represents the difference between the calibration performed with the four-terminal-pair fully-digital bridge and that performed with the traceability chain of the Italian national standard of capacitance. The uncertainty bars represent the expanded uncertainties with coverage factor  $k = 2$ .

that the bridge balance is fast and fully automated.

The bridge is validated by substituting the graphene ACQHR experiment, described in the next section, with a room-temperature  $12\,906.4\,\Omega$  resistance standard, in turn calibrated against the QHR in the DC regime.

The bridge validation is performed by determining the relative discrepancy  $\delta$  between the calibration of the  $8\,\text{nF}$  capacitor performed with the fully-digital bridge with that performed with the transformer-ratio impedance bridges employed in the current Italian traceability chain of farad (with an expanded uncertainty of about  $1.3 \times 10^{-7}$  [6]). Figure 3 shows the results of three comparisons. The uncertainty bars represent the expanded uncertainties with coverage factor  $k = 2$ . The average value of  $\delta$  is about  $2 \times 10^{-7}$ , that is, the same order of magnitude as the uncertainty of the four-terminal-pair fully-digital impedance bridge [11]. The main sources of uncertainty of digital bridges are the non-linearity of the digital signal generator, the not perfect realization of the impedance definition and the uncertainty of the standard employed in the calibration. The two calibration methods thus result compatible.

#### 4. – Graphene ACQHR experiment

Graphene devices simplify the implementation of the ACQHR experiment, requiring an experimental set-up operating at relatively low magnetic flux density and at the temperature of liquid helium.

The implementation of the ACQHR experiment at INRIM is based on a cryogenic probe equipped with a superconducting magnet able to operate at 5 T with a current

of 54 A. To reduce the effect of cable stray resistances and capacitances, multiple-connections [12, 13] are employed to connect the graphene device to the measurement system. These connections are commonly employed in DC QHR measurements. Their employment in the AC regime is supported by simulations with the SPICE circuit simulator [14] and with numerical analysis methods [15].

Due to other stray capacitive effects, the ACQHR shows narrower, distorted and shifted plateaus with respect to those measured in DC. These stray effects can be reduced with the double-shield technique [16], by placing the QHR between two rectangular shields connected to the high and low voltages of the device. This configuration ensures that the current lost through the stray capacitances crosses the device and contributes to the Hall voltage. The currents flowing in the QHR and in the capacitance standard are thus the same and the working condition of the ratio coaxial bridge is thus verified. According to this technique, the QHR is mounted on a TO-8 header equipped with auxiliary shields.

The system will be preliminary validated with a GaAs/AlGaAs device [17], which will be then replaced with an epitaxial graphene device grown on SiC [18, 19].

## 5. – Conclusions

A four-terminal-pair fully-digital impedance bridge can be employed to calibrate a capacitance standard directly against a QHR in the AC regime. A new traceability chain for the farad, simple and compact, can be realized with a fully-digital bridge and a graphene ACQHR. These methods can be employed also by minor metrology institutes and calibration laboratories.

\* \* \*

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