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Low frequency bridge for magneto-transport measurements of quantum anomalous Hall effect

Frédéric Overney[1], Juan Medved[2, 3] and Martina Marzano[2]
[1]Federal Institute of Metrology (METAS), Bern, Switzerland
frederic.overney@metas.ch
[2]Istituto Nazionale di Ricerca Metrologica (INRIM), Turin, Italy
[3]Politecnico di Torino (POLITO), Turin, Italy

***Abstract*—We present a low-frequency AC measurement bridge for magneto-transport characterization of quantum anomalous Hall effect devices under magnetic fields up to 10 T. Preliminary test performed on a graphene-based device shows an overall accuracy of the entire setup better than $150\,\mu\Omega/\Omega$ on the measurement of the Hall resistance.**

***Index Terms*—Bridge circuits, topological insulators, magnetoresistance, measurement techniques.**

I. Introduction

Following the redefinition of the International System of Units (SI) and the assignment of fixed numerical values to the Planck constant (h) and the elementary charge (e), the quantum Hall effect (QHE) and the Josephson effect can be de facto employed to achieve direct realizations of the unit of electrical resistance, the ohm (Ω), and the unit of electrical potential difference, the volt (V). Consequently, the direct realization of the unit of electric current, the ampere (A), is easily obtained by applying Ohm's law [1], [2].

The implementation of QHE resistance standards using GaAs devices requires the application of magnetic flux densities on the order of 10 T. This requirement can be relaxed when employing graphene devices, although magnetic fields of several T remain necessary to achieve well-developed QHE plateaus. Since the observation of the Josephson effect demands suppression of external magnetic fields, the concurrent realization of the QHE and the Josephson effect within a single device architecture presents an experimental challenge.

The discovery of the quantum anomalous Hall effect (QAHE) has renewed the prospects for electrical metrology by enabling the development of a comprehensive "quantum electrical metrology toolbox" capable of realizing quantum standards of resistance, voltage, and current within a single instrument. This opportunity arises from the fact that QAHE can be observed in the absence of an externally applied magnetic field, thus simplifying experimental conditions and enhancing the integrability of quantum electrical standards [3]. However, achieving quantization of the resistance necessitates operating the QAHE device at sufficiently low currents and temperatures, typically below 30 nA and 50 mK [4], [5].

The subsequent steps required to establish the QAHE as a practical resistance standard in metrology involve relaxing the stringent operating conditions, particularly with respect to allowable current and temperature ranges. The current European project "Quantum Anomalous Hall Effect Materials and Devices for Metrology (QuAHMET)" [6] is specifically designed to address these challenges. Within the project, METAS has developed a new measurement bridge dedicated to the systematic characterization of novel QAHE devices based on magnetically doped topological insulator thin films fabricated by the project partners. The objective of this bridge is not to realize high-accuracy measurements of the perfectly quantized QAHE resistance, but to perform magneto-transport measurements under magnetic fields up to 10 T, with a moderate target accuracy on the order of a few $100\,\mu\Omega/\Omega$.

This paper describes the operational principles of the bridge and reports the outcomes of the initial validation experiments conducted on graphene devices.

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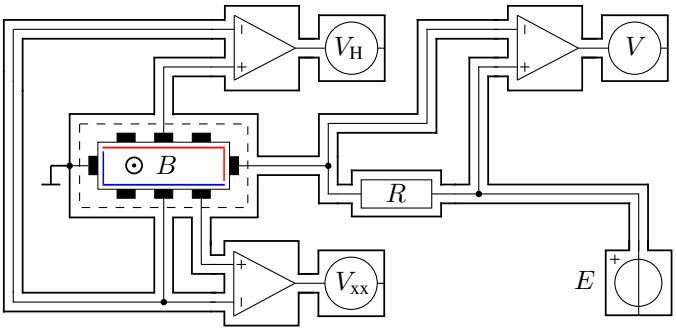


Figure 1. Bridge schematics designed for the characterization of the magneto-transport properties of the QAHE devices.

II. Bridge description and data processing

The sample is mounted on a TO8 socket integrated into the probe of a liquid-helium cryostat. The cryostat is equipped with a superconducting magnet capable of generating a magnetic field B in the range from -12 T to 12 T. Eight coaxial cables connect the TO8 socket to the top of the probe, thereby enabling electrical interfacing of the sample with the various measurement instruments. Figure 1 presents a schematic diagram of the measurement bridge. A voltage source, E, drives a current I_{rms} through a reference resistor $R = 100\,\mathrm{k}\Omega$, and the device under test (DUT) connected in series. Three digitizers synchronously record the voltage drop V across R, the Hall voltage V_{H}, and the longitudinal voltage V_{xx} across the DUT.

To avoid loading the DUT and thereby introducing systematic errors into the measurements, differential amplifiers with

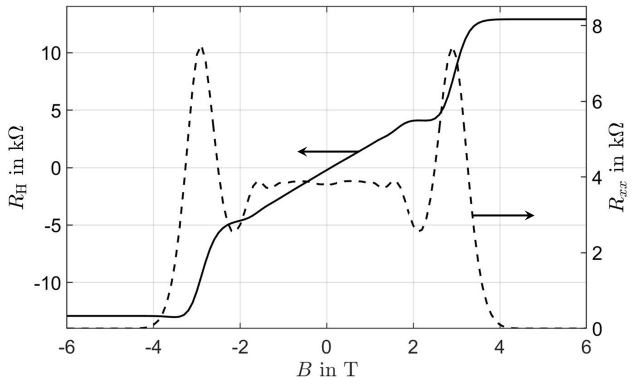


Figure 2. B dependency of R_{H} (solid line) and R_{xx} (dashed line) measured at 22 Hz and 100 nA on graphene device.

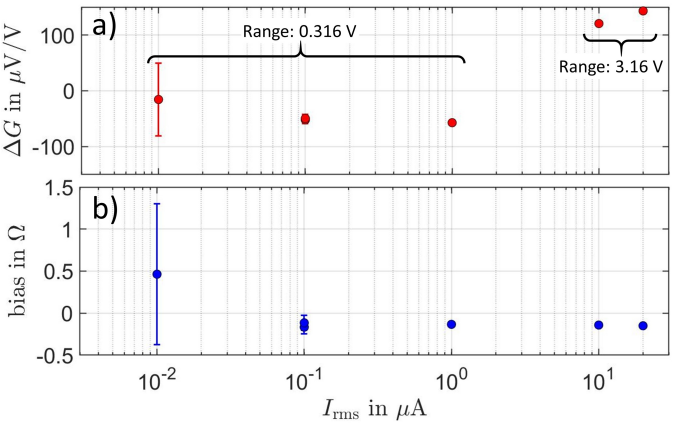


Figure 3. Current dependence of the gain error (a) and bias (b) of the bridge calculated from the QHE resistance measured at 22 Hz on the plateaus. The uncertainty bars correspond to the Type A uncertainties obtained over 10 measurements.

very low input bias currents are employed. To enhance the signal-to-noise ratio, the bridge is operated at a low alternating frequency. The digitizers synchronously acquire an integer number of periods of each voltage signal. A discrete Fourier transform is then applied to each dataset, and the amplitudes of the fundamental frequency components of the respective voltages are extracted. These amplitudes and the value of R are used to compute the Hall resistance $R_{\mathrm{H}} = R\ V_{\mathrm{H}}/V$ and the longitudinal resistance $R_{\mathrm{xx}} = R\ V_{\mathrm{xx}}/V$.

III. First Test on Graphene Sample

To evaluate the performance of the bridge, the magneto-transport properties of a graphene-based device (fabricated by PTB) were measured over the B range from $-6\,\mathrm{T}$ to $6\,\mathrm{T}$. Figure 2 shows R_{H} and R_{xx} measured at an excitation frequency of 22 Hz with $I_{\mathrm{rms}} = 100\,\mathrm{nA}$ across the entire B range. For $|B| \geq 5\,\mathrm{T}$, R_{xx} vanishes indicating that the R_{H} regime is established above this threshold. In principle, the gain error associated with each individual measurement channel—including contributions from cables, the differential amplifier gain, and the analog-to-digital converter (ADC) gain—as well as the reference value of R, should be characterized by dedicated calibration procedures. Nevertheless, the transport properties of the graphene device can be utilized to determine the aggregate measurement error of the complete experimental setup, thereby eliminating the necessity for separate calibration of each constituent component. The bias and gain error ΔG of the whole measurement chain can be determined by

$$\Delta G = \frac{\bar{R}_{\mathrm{H}}(B>5) - \bar{R}_{\mathrm{H}}(B<-5)}{R_{\mathrm{K}}} - 1$$
$$\mathrm{bias} = \frac{\bar{B}_{\mathrm{H}}(B>5) + \bar{R}_{\mathrm{H}}(B<-5)}{2},$$

where $\bar{R}_{\mathrm{H}}(B>5)$ is the mean value of R_{H} measured at $B > 5\,\mathrm{T}$ and R_{K} the von Klitzing constant.

Figure 3 presents ΔG and bias of the setup, characterized at 22 Hz for I_{rms} from 10 nA to 20 µA. ΔG exhibits two distinct levels as a function of I_{rms}, which is attributed to the use of two different full-scale ranges in the ADCs, causing a discontinuity between 1 µA and 10 µA. Despite this discontinuity, this preliminary assessment indicates that the overall uncertainty of the system remains better than $150\,\mu\Omega/\Omega$. A small systematic deviation of less than $0.5\,\Omega$ is observed over the entire current range. A more comprehensive characterization of the bridge, together with initial measurement results obtained on QAHE devices, will be presented at the conference.

IV. Conclusion

We developed a low-frequency AC bridge tailored to systematic magneto-transport measurements of emerging QAHE devices with moderate target accuracy. Synchronous digitization combined with discrete Fourier analysis enables robust extraction of R_{H} and R_{xx} while minimizing loading of the DUT. Initial validation on a graphene quantum Hall device demonstrates bridge performance better than $150\,\mu\Omega/\Omega$ over a wide current range, supporting its use for rapid characterization across magnetic field and temperature parameter spaces.

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