Ultrastable Low-Noise Current Amplifiers With Extended Range and Improved Accuracy

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Abstract — **The ultrastable low-noise current amplifier (ULCA) was developed as an advanced instrument for the improved measurement of currents generated by single-electron transport (SET) devices. It was optimized for direct currents in the picoampere range, and achieves an uncertainty of about 0.1 parts per million for a current of 100 pA, typically generated by SET pumps. This paper summarizes our efforts in extending the ULCA's current range and minimizing the measurement uncertainty over a wide range. The final goal is to obtain a universal instrument for measuring and generating direct currents between about 1 fA and 1 µA with unmatched accuracy.**

Index Terms — **Calibration, current measurement, low-noise amplifiers, measurement standards, measurement uncertainty.**

I. Introduction

The ultrastable low-noise current amplifier (ULCA) was developed as a novel instrument for small direct currents [1] – [3]. Besides current measurement, it allows current generation as well as the calibration of high-value resistors with unmatched accuracy. The ULCA was originally optimized for the measurement of currents generated by single-electron transport (SET) devices. It achieves uncertainties of about 0.1 parts per million (ppm) at 100 pA and has a dynamic range of ±5 nA. At very small currents below about 1 pA, the total measurement uncertainty is typically dominated by the ULCA's input current noise of 2.4 fA/$\sqrt{\mathrm{Hz}}$. This paper reports the current status of our work towards minimized uncertainty in an extended current range of 1 fA to 1 µA.

II. Effect of Resistor Nonlinearity

The ULCA involves two amplifier stages, the first (input stage) providing current amplification with gain $G_I = 1000$ and the second (output stage) performing a current-to-voltage conversion via a highly stable 1 MΩ resistor. The resulting transresistance (output voltage versus input current) is A_{TR} = 1000×1 MΩ = 1 GΩ. In the initial design, the 1000-fold current amplification is realized with a special network of about 3000 individual 2 MΩ chip resistors in case size 0805 (2 mm × 1.25 mm), wired as a matched resistor pair of 3 GΩ and 3 MΩ [1]. As a result, this device (denoted in the following as "3 GΩ ULCA") features a noise level of 2.4 fA/√Hz and a dynamic range of ±5 nA. A high-accuracy variant with 200 kΩ chip resistors was also realized [1]. It was supposed to lead to a corresponding improvement in the overall accuracy. However, the increased noise level of 7.5 fA/$\sqrt{\mathrm{Hz}}$ (resulting from the tenfold reduction in total resistance to 300 MΩ) made this variant unattractive at the present phase, where noise typically limits the overall uncertainty in SET experiments.

A preliminary uncertainty budget for the 3 GΩ ULCA with conservative estimates of the uncertainty contributions was presented in [2]. According to the assumptions made, an uncertainty of about 0.06 ppm is achieved if the ULCA is calibrated shortly before or after a measurement with PTB's 14-bit cryogenic current comparator (CCC). The overall uncertainty in the preliminary uncertainty budget presented in [2] was dominated by unknown nonlinearity effects in the ULCA resistor network. In case of the 3 GΩ ULCA, the resistor nonlinearity cannot be measured with sufficiently low random uncertainty, even if PTB's 14-bit CCC is used that exhibits a very low current noise level in the relevant frequency range. Therefore, the nonlinearity of a 300 MΩ network was investigated instead, taking advantage of the 10-fold current range as compared to the 3 GΩ variant.

Figure 1 shows the dependence of the nonlinearity error ΔG_{NL} on the peak input current I_{P}. The solid line is a quadratic fit from which a power coefficient of resistance (PCR) of -20500 ppm/W is deduced for the individual size-0805 chip resistors mounted on the network board. A temperature coefficient of resistance (TCR) of -10 ppm/K was estimated from measurements of resistor samples, which results in a thermal resistance of 2050 K/W per chip resistor at the low-ohmic part of the network (the power dissipation per resistor at the high-ohmic part is a factor of 1000 smaller and therefore negligible). In order to minimize leakage currents, as much material as possible had been milled away from the printed-circuit board carrying the resistors. This strongly reduces the cooling of the chip resistors and presumably causes the atypically high thermal resistance. Applying the thermal model to the 3 GΩ network results in a nearly fivefold reduction of the contribution from resistor nonlinearity compared to our previous estimate, which relied on an assumed voltage coefficient of < 0.1 ppm/K. In this case, the total calibration uncertainty is improved to about 0.04 ppm.

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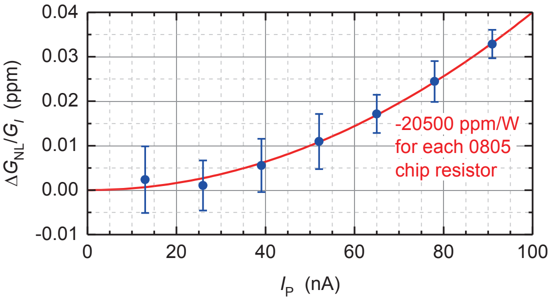

Fig. 1. Nonlinearity of a 300 MΩ network measured with the 14-bit CCC versus input current amplitude I_P. The current was reversed every 10 s, and the first 5 s after each reversal were disregarded. The data points represent the mean of 2 to 4 independent measurements taken with a sequence that reduces drift effects. At low currents, longer sampling times were chosen to lower the uncertainty, resulting in a total averaging time of nearly 9 hours. Blue dots show measured data, the red solid line is a quadratic fit yielding a PCR of the individual size-0805 chip resistors of -20500 ppm/W. The chosen reference value for the gain nonlinearity ΔG_{NL} constrains the fit curve to pass through the origin. Error bars show type A standard uncertainties.

To check the proposed thermal model for resistor nonlinearity, the current gain of a 3 GΩ network was calibrated with the 14-bit CCC alternately at ±6.6 nA and ±13 nA input current. Changing the current from ±6.6 nA to ±13 nA increases the power dissipation in each 2 MΩ resistor at the low-ohmic part of the network by about 0.25 µW, leading to a temperature rise of about 0.5 mK. Assuming a TCR of about +10 ppm/K (estimated from sample measurements), this results in an expected gain change of about -0.005 ppm. The measured gain change of (-0.003 ± 0.008) ppm obtained for a total averaging time of 10½ hours is consistent with the nonlinearity model predicted from thermal effects. As a consequence of the findings, “high-current” ULCA variants should be designed with lower current gain to minimize nonlinearity from temperature effects in the resistors.

III. Range Extension

For currents within the standard ±5 nA dynamic range, the 3 GΩ ULCA is operated conventionally with both input and output stages [1]. To extend the dynamic range from ±5 nA up to ±5 µA, the output stage can be applied without current amplification by the input stage, and the latter is wired such that it does not affect the output signal. The corresponding configurations are depicted in Fig. 2. The current noise level is substantially increased to about 160 fA/$\sqrt{\mathrm{Hz}}$ with a $1/f$ corner at about 10 mHz. However, for high currents this is not an issue. At the lowest current of ±5 nA, the ULCA’s contribution to the type A standard uncertainty is 0.42 ppm for a measurement of one hour. In the case of current generation according to Fig. 2(b), the ULCA’s 1 MΩ resistor is not connected to the output of amplifier OA2, and the latter is grounded to form a servo loop that keeps the current output terminal IRET at internal ground potential (triangles in Fig. 2).

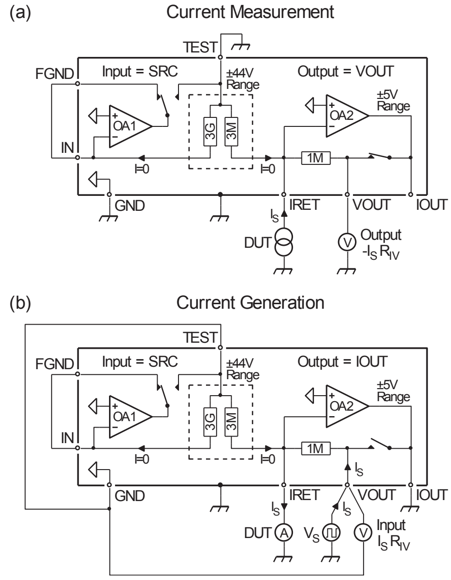

Fig. 2. Configurations for extending the current range of the 3 GΩ ULCA up to ±5 µA. (a) Current measurement with a current source as device under test (DUT), (b) current generation with an amperemeter as DUT. In (b) a star-shaped wiring for voltage source V_S and voltmeter is recommended to minimize parasitic series resistance.

First measurements with the described range extension are presented in [4]. ULCA variants with 100-fold current gain, allowing lower noise levels and uncertainties in the nanoampere range, are currently under development.

IV. Conclusion

The ULCA is a user-friendly and superior alternative to existing meter and source instruments for small direct currents. With further improvements, standard uncertainties down to about 0.02 ppm seem achievable for currents in the nanoampere range. The measurement uncertainty and/or time can be further reduced in the femtoampere range by lowering the noise to the projected level of ≈ 0.6 fA/$\sqrt{\mathrm{Hz}}$. It is, therefore, expected that these developments will set new accuracy benchmarks in the current range between ±1 fA and ±1 µA.

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