Cable Noise Investigations for High-Accuracy Measurements of Small Direct Currents

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***Abstract*—Single-electron experiments may provide possible realizations of the future SI ampere if they are performed at high accuracy corresponding to 0.1 ppm uncertainty or better. However, excess noise in the cabling between the room temperature equipment and the cryogenic quantum current source, typically mounted inside a refrigerator setup, limits the achievable accuracy. We present amplifier tools for precise noise investigations and first results of measurements on different cable specimens as starting point for a systematic study on the topic.**

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

I. Introduction

The possibility of realizing the future SI ampere with quantum current sources based on single-electron transport (SET) devices is getting within reach with the advent of 'self-referenced' SET pumps [1]. SET pump devices typically are operated in cryogenic refrigerators and are able to source currents of the order of 100 pA. Current quantization according to $I = e\,f$ recently has been confirmed at an accuracy level corresponding to 0.2 ppm relative standard uncertainty [2] by using a new superior type of small-current amplifier [3]. Metrological applications demand that the current sourced by such pump is transferred via cables (typical length more than 1 m) to current amplification or measurement instrumentation located outside the refrigerator setup. With increasing accuracy of the SET pumps (aiming at 0.1 ppm or better), noise from the cabling inside and outside the refrigerator becomes crucial and limits the performance of the experiments. Minimization of such parasitic effects in the small-current signal paths is, therefore, needed. We pursue systematic investigations in order to find an optimal cabling solution. For this purpose we developed a new amplifier, and present first measurements on different cables.

II. Low-Noise Current Amplifier

The central tool for our investigations is a newly developed ultra-low noise current amplifier with ppm-level accuracy that is based on the concept of the ultrastable low-noise current amplifier (ULCA) [3]. The initial prototype showed an effective white noise level of about $0.7\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$. After further design optimization, the final amplifier reached a white noise level of $0.43\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ and an input bias current of about 0.6 fA at 23 °C. Figure 1 shows an Allan deviation plot of the amplifier signal. The measurement was done in a laboratory without temperature stabilization, resulting in peak-peak temperature fluctuations of about 1 K. A temperature coefficient of about 0.33 fA/K was determined from the corresponding fluctuations in the amplifier output, and was used together with the amplifier's internal temperature sensor for suppression of temperature effects. The red curve in Fig. 1 is calculated from the white noise level and $1/f$ corner frequency deduced from the measured noise spectrum. It is in good agreement with the Allan data, except for $\tau < 10\,\mathrm{s}$ due to an increase of the noise level above about 0.1 Hz, presumably caused by parasitic capacitance in the amplifier design. The amplifier enables reaching 20 aA current resolution after 400 s with a stability over at least one day. Besides being an excellent tool for cable noise investigations, this amplifier is also useable for the characterization of SET pump devices at ppm accuracy level in relatively short measurement times.

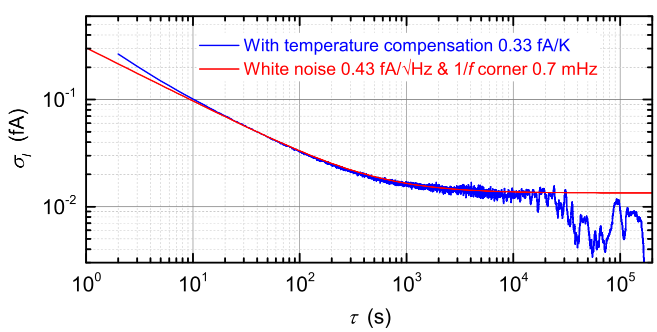

Figure 1. Allan deviation plot of the amplifier signal. Effects caused by temperature fluctuations are compensated by taking into account the amplifier's temperature coefficient of 0.33 fA/K. The red fit curve is calculated from the measured noise spectrum. For the measurement, a total transresistance A_{TR} of 1 TΩ was chosen.

III. Cable Measurements

Recently published work, setting a new benchmark in high-accuracy SET pump measurements, was performed in a dilution refrigerator setup. The total noise level was about $3.5\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ to $4.5\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ [2]. Given the ULCA noise level of $2.4\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ [3], the dominant noise contribution of $2.5\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ to $3.8\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ most likely originates from the wiring. Thus, the cable noise contribution was of similar magnitude as the noise from the measurement instrumentation.

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Consequently, further accuracy improvement requires reduction of noise in the signal path comprising room temperature and cryogenic cabling.

A. *Coaxial Cables for Room Temperature Applications*

For typical SET experiments, a cable at room temperature is needed to connect the dipstick inside the cryogenic refrigerator with the current amplifier. Low-noise coaxial cables for room temperature applications are commercial available. Typically, they are equipped with a conductive layer between dielectric and shield to reduce noise caused by triboelectric effects (see, for instance, reference [4]).

Noise measurements on four different coaxial cables with similar construction were performed (Table I). Three of them were equipped with polytetrafluoroethylene (PTFE) as dielectric except of cable (C) that uses polyethylene (PE). Power spectra of open-ended cable segments of 2 m length (shielded with cover caps) were measured between 1 mHz and 1 Hz, see Fig. 2. Apparently the noise levels of the cables are quite different at frequencies below about 0.1 Hz, i.e. in the frequency range relevant for typical direct current measurements. The approximate noise levels at 10 mHz (corrected for the amplifier's contribution) are listed in the bottom row of Table I. Cables (A) and (C) show the best results. Cables (A) and (B) are from the same manufacturer and similar in construction, however, they differ in the construction of the conductive layer: in cable (A) the conductive layer is very smooth, so that the braided copper shield can easily slide over this layer. Cable (B) has a patterned conductive layer, making it difficult for the shield to slide. It appears that this difference in construction strongly affects the low-frequency noise characteristics. Allover, cable (C) with PE as dielectric shows the most preferable performance (lowest noise) from this selection of cables.

Table I
FOUR INVESTIGATED LOW-NOISE CABLES

Label	(A)	(B)	(C)	(D)
Cable type	elspec LN5001	elspec LN5002	bedea MXR	FEMTO CAB-LN1
Inner conductor	Steel copper silver-coated	Steel copper strand silver-coated	Copper strand	Copper strand
Dielectric	PTFE	PTFE	PE	PTFE
Shielding	Semi-conductor & silver-coated copper braid	Semi-conductor & silver-coated copper braid	Conductive PVC & copper braid	Semi-conductor & silver-coated copper braid
Sheath	PFA	PTFE-T	PVC	PFA
Noise at 10 mHz	≈ 0.7 fA/$\sqrt{\text{Hz}}$	≈ 5.6 fA/$\sqrt{\text{Hz}}$	≈ 0.5 fA/$\sqrt{\text{Hz}}$	≈ 1.9 fA/$\sqrt{\text{Hz}}$

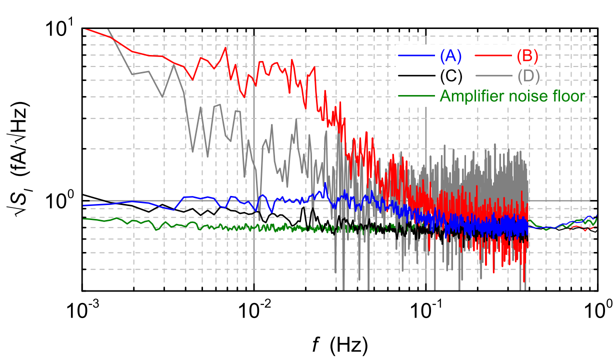

Figure 2. Current noise levels of four different 2 m long cables measured with the low-noise current amplifier prototype (0.7 fA/$\sqrt{\text{Hz}}$ white noise). The noise level of (B) and (D) strongly increases at frequencies below about 0.1 Hz, while (A) and (C) show only small degradation. The best cable (C) has PE as dielectric.

B. *Cables Suitable for Cryogenic Systems*

For cryogenic systems the requirements for cables are more demanding. Typically the cable has to bridge a temperature gradient from mK to room temperature, which can cause mechanical stress. This may induce slipping of the inner (current carrying) conductor in the dielectric insulator material, which again may enhance parasitic (triboelectric) effects hampering the noise performance. Furthermore, the cooling capability of the refrigerator is limited. Hence the heat load introduced by the cable has to be as low as possible. Furthermore, vacuum pumps or pulse tube elements in the refrigerator systems usually cause vibrations, which also leads to elevated cable noise.

IV. CONCLUSION

Cable noise measurements at room temperature were performed with a specially designed low-noise current amplifier. Based on a preliminary selection of four different coaxial cable types, it was found that the low-frequency noise levels significantly differ. Careful choice of cables is, therefore, crucial for high-accuracy measurements of small direct currents. From the given set of cables, the one with PE dielectric insulation shows the best result in terms of noise.

The combination of a new type of low-noise amplifier and the PE insulated cable is considered providing a suitable testbed for further investigations. The work to follow will pursue the identification and/or construction of cables suitable for cryogenic applications in SET experiments. First results will be presented at the conference.

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