

# Multistage RF filtering system for ultralow temperature nanoelectronic experiments

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**Abstract.** Cryo-filters are essential while studying electronic properties of nanoscale structures at very low temperatures. In this report we present the simple measuring methodology and experimental impedance characteristics of customized lumped filters cooled down to 4.2K in the 10 Hz-500 MHz frequency range. In particular, we tested the home-made permalloy-core RL filters, the Murata<sup>TM</sup>Chip Ferrite Bead EMI filter, and the Toshiba<sup>TM</sup>Amobeads<sup>TM</sup>cores. We use the high-frequency generalization of Kelvin sensing method to account for the wiring retardation effects, which are important when working with ultralow temperature systems.

## 1. Introduction

While electron transport measurements at ultralow temperatures ( $T < 100$  mK) rather small external disturbances might lead to a noticeable overheating. The inevitable external EMI noise, picked-up and transmitted through electric wires, results in a mismatch between the electron  $T_e$  and the phonon  $T_{ph}$  temperatures  $P \sim W(T_e^5 - T_{ph}^5)$ , where  $P$  is the power dissipated at the sample with volume  $W$ [1]. Hence, for sufficiently small nanoelectronic systems the effect might be clearly pronounced. Multiple methods have been suggested to reduce the undesired electron heating [2]. Among them, the utilization of various RF filters to cut the impact of noisy EMI environment is the most common ones. So far this problem remains relevant [3, 4, 5, 6, 7]

To measure an RF filter' characteristics typically rather expensive broadband network analyzers should be used. The test sample needs to be directly connected to the analyzer via special certified cables, that is only possible for measurements conducted at room temperature. To make measurements at low temperatures, where filter' characteristics can change dramatically, it is necessary to use specific cryo-wiring that may dramatically skew the results, especially at high frequencies.

Here we describe a simple measuring method to experimentally obtain impedance-frequency characteristics of several home-made and customized filters for nanoelectronic studies at very low temperatures.

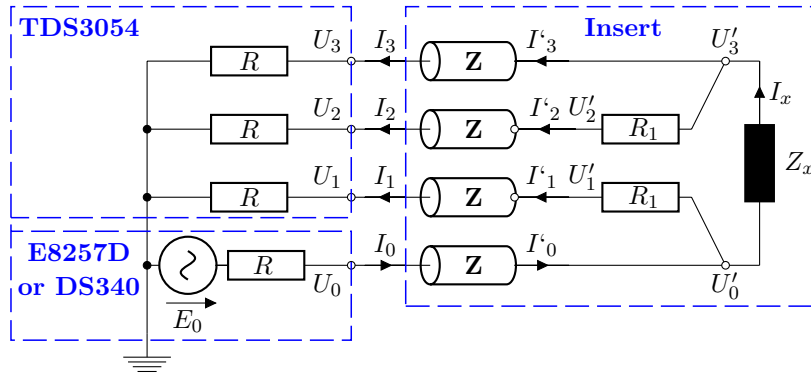
## 2. The measuring scheme

For testing filters we use top loading insert that operates in a standard liquid helium transport dewar with 12 mm bore. The sample is mounted in a cylindrical copper shielded box at the bottom of the insert.

The schematic diagram of the measurements is presented in Fig.1.

To measure the frequency response of samples we use the 4-channel oscilloscope Tektronix<sup>TM</sup>TDS3054 with sampling rate of 5GS/s, 500 MHz bandwidth, and simultaneous recording of  $10^4$  readings per channel with 9-bit resolution. This gives us the ability to find amplitudes and phases of the signals  $U_1, U_2, U_3$  (Fig. 1). The signal  $U_0$  can be used for control and synchronization.

As RF signal source we use Agilent Technologies<sup>TM</sup>PSG CW signal generator E8257D (for high frequencies) and Stanford Research Systems<sup>TM</sup>15 MHz synthesized function generator DS340 (for lower frequencies). In our case, characteristics of the oscilloscope are significant. As for the RF source it does not impose any special requirements, and it can be replaced by any appropriate device.



**Figure 1.** Schematic of the experiment.  $R=50$  Ohm corresponds to oscilloscope and oscillator impedances.  $R_1=250$  Ohm, corresponds to low inductance metal resistors.  $\mathbf{Z}$  stands for 1.2 meter-long coaxial cables (PK50-0,6-23).

In this work we deal with lumped filter samples. To test them at liquid helium temperatures we need to use cables and account for their retardation effects. We can circumvent this limitation by introducing the complex current/voltage transformation matrix  $\mathbf{Z}$  :

$$\begin{bmatrix} U'_k \\ I'_k \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & |Z| \sinh(\gamma l) \\ \frac{\sinh(\gamma l)}{|Z|} & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} U_k \\ I_k \end{bmatrix}, \quad k = 0..3.$$

where  $\gamma$  denotes the complex propagation constant,  $l$  is the length, and  $|Z|$  is the characteristic impedance of the cable. Using condition  $I_k = U_k/R$ ,  $k=1..3$  we get:

$$U'_k = \left( \cosh(\gamma l) + \frac{Z}{R} \sinh(\gamma l) \right) U_k \equiv a \cdot U_k, \quad I'_k = \left( \frac{1}{Z} \sinh(\gamma l) + \frac{1}{R} \cosh(\gamma l) \right) U_k \equiv b \cdot U_k$$

Given that  $U'_2 - U'_3 = I'_2 R_1$ , and  $U'_1 - U'_0 = I'_1 R_1$  we end up with a simple expression for the complex impedance  $Z_x$  as function of complex parameters  $U_1, U_2, U_3$ , whose amplitudes and phases are determined from the measured signals:

$$Z_x = R_1 \frac{(U_1 - U_2)U_3}{(U_3 - U_2)(U_3 + U_2)} \quad (1)$$

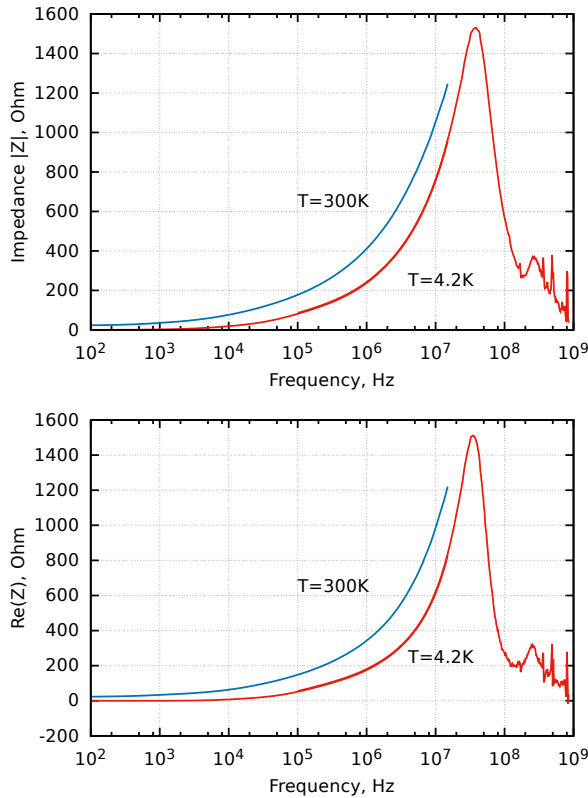
The fact that all four cables are identical allowed to exclude their properties from the expressions. Moreover, the result does not depend on amplitude of the testing signal, which allows the usage of simple non-stabilized generators.

### 3. Frequency characteristics of various filters

Cryostat for ultralow temperature experiments should be equipped with a multistage filtration system which may consist of EMI filters at room, as well as, liquid He temperatures. One may add also some cryogenic low-pass filters thermally anchored to 1-K pot, to mixing chamber and experimental cell. Our task was to measure characteristics of various filters to evaluate the possibility of their usage in a multi-stage filtration system.

#### 3.1. Permalloy-core inductor (RL filter).

For fabrication of the magnetic core we used permalloy tape with thickness of 0.1 mm and width of about 11 mm, which was wound on a cylindrical template, forming the magnetic core of a toroidal shape inductor with ID 2 mm, and OD 4.5 mm. The core was annealed in vacuum. On that core 20 turns of a NbTi/CuNi superconducting wire of 0.1 mm diameter were wound forming an inductance with room temperature DC resistance  $R_{DC} = 23 \Omega$ .



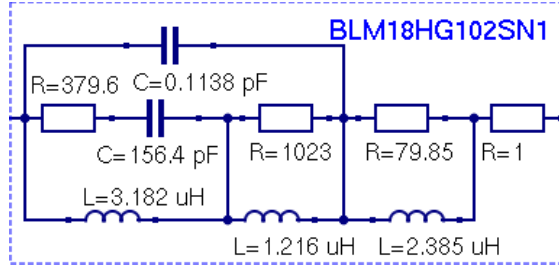
**Figure 2.** Measured frequency characteristics of the custom-made inductor with permalloy core: the amplitude values  $|Z|$  of the impedance (left); real  $Re(Z)$  and imaginary  $Im(Z)$  parts of impedance (below). In all three graphs the upper (blue) line represent the data obtained at room temperature and lower (red) lines represent the data obtained at 4.2K.

One can notice that despite the expected pure reactive behavior of our filter, it is resistive in the range of 10 – 50 MHz, which can be explained by eddy currents in permalloy. It is the positive observation for the filtering problem, though it is evident, that our filter design is far from optimal.

#### 3.2. Murata<sup>TM</sup> Chip Ferrite Bead EMI suppression filter

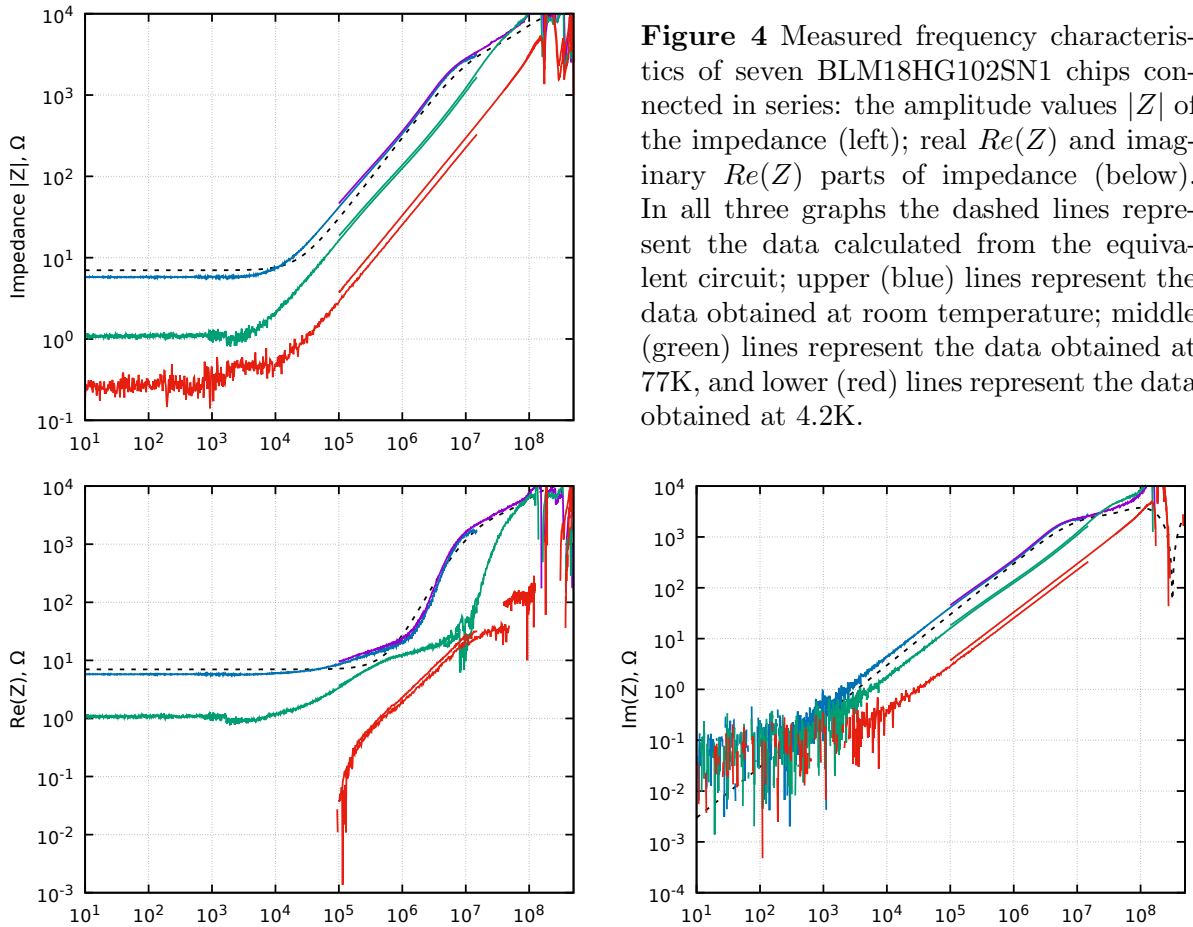
EMI suppression filters from Murata<sup>TM</sup> are widely used in modern electronics as a universal noise suppression component for frequencies ranging from a few MHz to a few GHz. They are easily available, cheap and well documented. Chip Ferrite Bead acts like a micro inductance in the low frequency range. At high frequencies, however, the resistive component of the inductor constitutes the main part of the impedance. (See [www.murata.com](http://www.murata.com) site).

For testing we choose the product BLM18HG102SN1 which is a EMI suppression filter of the Ferrite Beads type.



**Figure 3.** Equivalent circuit for BLM18HG102SN1 filter based on the parameters listed in SPICE model netlist. The manufacturer indicates the following information for the product:

- Shape: 0603 SMD.
- Operating temperature: ( $-55$  to  $125^{\circ}\text{C}$ ).
- DC resistance:  $1.6\ \Omega$ .
- Impedances at  $100\ \text{MHz}$  and  $1\ \text{GHz}$ :  $1\ \text{k}\Omega$ .



**Figure 4** Measured frequency characteristics of seven BLM18HG102SN1 chips connected in series: the amplitude values  $|Z|$  of the impedance (left); real  $\text{Re}(Z)$  and imaginary  $\text{Im}(Z)$  parts of impedance (below). In all three graphs the dashed lines represent the data calculated from the equivalent circuit; upper (blue) lines represent the data obtained at room temperature; middle (green) lines represent the data obtained at  $77\text{K}$ , and lower (red) lines represent the data obtained at  $4.2\text{K}$ .

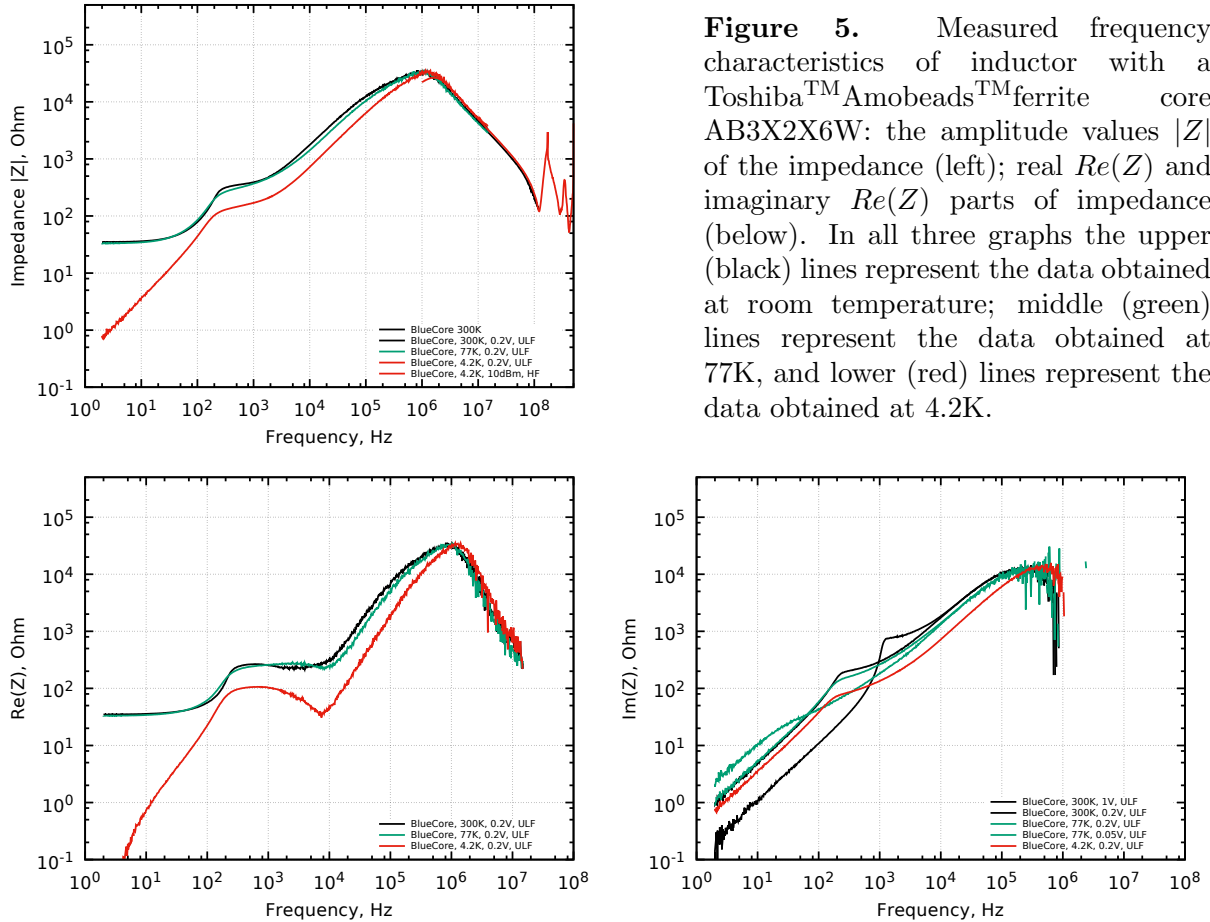
It is worth noting the excellent agreement between the measured room-temperature data and the calculated values.

### 3.3. *Toshiba<sup>TM</sup> Amobeats<sup>TM</sup> ferrite core AB3X2X6W*

The amorphous noise suppression devices, AMOBEADS<sup>TM</sup>, suppress rapid changes in current which could otherwise lead to electrical noise in various circuits. Because of their square-shaped magnetic hysteresis behavior, amorphous noise suppression devices provide very large inductance when the current crosses zero (i.e. changes sign). This large inductance effectively blocks any further current changes. (See <https://toshiba.semicon-storage.com>)

For testing we choose the ferrite core AB3X2X6W which is an amorphous noise suppression device. We were unable to find the manufacturer information about the minimal working

temperature for this product but suspected that it can be low. The core has a cylindrical shape 4mm OD with an axial channel of 1.5 mm ID ; its length is 7.5 mm. For fabrication of the RL filter we wound 50 turns of a NbTi/CuNi superconducting wire of 0.1 mm diameter. The resistance of this coil comprises 36 Ohms.



**Figure 5.** Measured frequency characteristics of inductor with a Toshiba<sup>TM</sup>Amobeads<sup>TM</sup>ferrite core AB3X2X6W: the amplitude values  $|Z|$  of the impedance (left); real  $Re(Z)$  and imaginary  $Im(Z)$  parts of impedance (below). In all three graphs the upper (black) lines represent the data obtained at room temperature; middle (green) lines represent the data obtained at 77K, and lower (red) lines represent the data obtained at 4.2K.

In the low frequency region, the sample has the nonlinear current-voltage characteristics, which is manifested in the form of a hump on the curves near 200 Hz. With the increase of the signal amplitude, the position of the hump moves towards higher frequencies, and its height increases.

#### 4. Conclusions

We have developed a simple method of measuring the frequency dependence of electrical impedances in a wide (10 Hz-500 MHz) frequency range without usage of expensive network analyzers.

The method enables measurements to be made on samples cooled down to low temperatures.

As an example of using the method, Murata<sup>TM</sup>Chip Ferrite Beads EMI filters and Toshiba<sup>TM</sup>Amobeads<sup>TM</sup>cores, whose low temperature characteristics were not rated previously, were measured. It was found, that in series connected Murata<sup>TM</sup>BLM18HG102SN1 chips may serve as a high-efficiency EMI filter at room, as well as, liquid nitrogen temperatures. As for Toshiba<sup>TM</sup>Amobeads<sup>TM</sup>ferrite cores, they are useful to block rapid-transition currents (spikes) at room, as well as, at liquid He temperatures.

We also tested a permalloy-based RL filter, and found, that it is promising, but needs to be optimized.

## Acknowledgments

The experimental studies and theory assessment of the results were supported by Russian Science Foundation (project No.16-12-10521). Fabrication of the RL filters was made by students S. A. Chernyaev, K. V. Shein and A. G. Shukaleva, who acknowledge the support of Higher School of Economics project No.16-05-0029 "Physics of low-dimensional quantum systems".

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