AIP | Review of Scientific Instruments

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Citation: Review of Scientific Instruments **83**, 064703 (2012); doi: 10.1063/1.4725526
View online: http://dx.doi.org/10.1063/1.4725526
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/83/6?ver=pdfcov
Published by the AIP Publishing

Electrometric direct current I/V converter with wide bandwidth

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(Received 27 October 2011; accepted 17 May 2012; published online 12 June 2012)

A principle of operation and electrical characteristics of a high frequency current-to-voltage (I/V) converter are presented. The I/V converter measures the electric current with selectable gains of 10^5, 10^4, and 10^3 V/A in the frequency range from DC to 500 kHz, 1.2 MHz, and 2.4 MHz, respectively. These properties make this I/V converter suitable for wide range of applications such as tuning forks, torsion oscillators, ultrasound transducers measurements, detection of the piezoelectric transducers used in STM techniques, etc., in low temperature physics. The influence of the input impedance of a I/V converter on the precision of alternating current measurements is also discussed. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4725526]

INTRODUCTION

A fundamental feature of any active current-to-voltage (I/V) converter is a very high value of the differential impedance R_D, which together with a very small bias current and low noise current, in principle determine minimal amount of the electric current being detected. The simplest and typical scheme of the I/V converter is very well known (see Fig. 1). This is an electrometric type of the operational amplifier (OA) working as an active device with a resistor R_F (typical value of R_F is the order of 10^8 Ω) and capacitor C_F connected in parallel in negative feedback providing the high amplification and frequency stability.[1] The electrometric type of the OA offers an extremely high impedance of input transistors and very low bias current of the order of 50 fA. However, the high amplification provided by the feedback impedance Z_F reduces the frequency bandwidth of the measured current signals to a range of typically from DC to 100 kHz. This reduction is due to a time constant $\tau = R_F C_F$. The high frequency OAs, on the other hand, offer a lower differential input impedance, but a broader frequency bandwidth than the electrometric counterparts. A combination of the electrometric JFETs (or MOSFETs) with high frequency OAs allows a design of the I/V converters operating in a broader frequency range from DC up to a few MHz.

There are many applications, e.g., measurements of high impedance devices such as ultra sound piezo-electronic transducers used in "surface" microscopy (SPM, AFM, etc.)[2,3] and tuning forks, torsion oscillators, electrostatically driven grids, etc., are another types of very useful experimental tools used for study of physical properties of quantum liquids (^{3}He, ^{4}He, and their mixtures) and other systems at low and very low temperatures.[4–6] Information about a physical system investigated by any of above mentioned techniques is obtained by observing electric current, which is usually detected by means of a I/V converter. Aims of this article are (i) to focus the attention of experimenters on fundamental properties of the real I/V converters (in particular, its input impedance), which are not so obvious from electric schemes, but they may affect precision or even distort the measurements (especially at higher frequencies), and (ii) to present properties of a high frequency I/V converter suitable for wide range of above mentioned applications.

As shown in Ref. 7, the precise measurements of alternating currents flowing through above mentioned devices require reduction of the input impedance of the I/V converter Z_{in}. Although it seems from Fig. 1 that the input impedance of the I/V convertor should be zero as the inverting input has a potential of a "virtual" ground, it is easy to show that the input impedance Z_{in} of any real I/V converter can be expressed as ($R_D \gg R_F$)

$$Z_{in}(\omega) = \frac{Z_F(\omega)}{1 + A(\omega)} \doteq \frac{Z_F(\omega)}{A(\omega)}, \qquad (1)$$

where $Z_F(\omega) = R_F/(1 + j\omega R_F C_F)$ and $A(\omega) = A(0)/(1 + j(\omega/\omega_{3dB}))$ is the gain of the OA with $A(0)$ being the DC open loop gain of OA and ω_{3dB} is the frequency bandwidth of the OA (f_{3dB}) multiplied by 2π. For comparison, the input impedance Z_{in} of an ideal I/V converter (ideal OA with $A(\omega) \to -\infty$) equals to zero.

The input alternating current flowing through non-zero input impedance of the I/V converter connected in parallel to the capacity of the input coaxial cable C_{in} generates the voltage, which causes "a current leakage" via C_{in}. Then the I/V converter detects the smaller current by factor $1/(1 + j\omega C_{in} Z_{in})$. As it follows from expression (1), at low frequencies, a typical gain factor of the operational amplifier $A(0)$ is of the order of 10^5 and taking $Z_F \doteq R_F = 10^8\,\Omega$, then, the input impedance of the I/V convertor is $Z_{in} \doteq R_{in} = 10^3\,\Omega$. When the angular frequency of the input current increases above ω_{3dB}, the input impedance Z_{in} becomes larger due to the degradation of $A(\omega)$ with higher angular frequency. The higher value of R_F increases the gain of I/V convertor on one side, but on the other it reduces its frequency bandwidth (see expression for $Z_F(\omega)$) and increases its input impedance, Z_{in}, as well. The value of the I/V converter output

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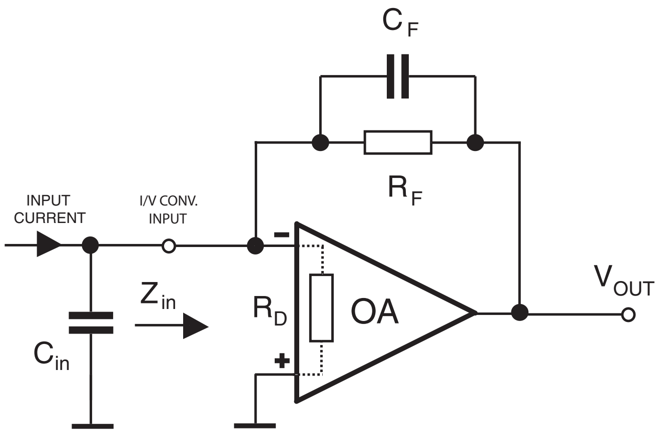

FIG. 1. The simplest implementation of the I/V converter.

voltage can expressed as

$$V_0(\omega) = \frac{-Z_F(\omega)I(\omega)}{1 + \frac{Z_{in}(\omega)}{X_c(\omega)}}, \tag{2}$$

where $I(\omega)$ is the input current and $X_C = 1/(j\omega C_{in})$ is already mentioned capacitance of the input cable. The input impedance of the I/V converter, Z_{in}, forms a voltage divider with the effective series impedance of the device under test (DUT) in Fig. 2, representing the impedance of the transducer or device being measured. Thus, the voltage across the device being measured is not the same as the excitation voltage provided by the voltage source (see Fig. 2), due to the voltage drop across the input terminals. This may result in additional error, especially, when the high Q devices are measured and, in order to minimize this error, the input impedance of the I/V converter Z_{in} should be much smaller than the impedance of the device being measured.

In this article we present the principle of operation and the properties of a relatively simple I/V converter designed as a combination of a dual JFET and high frequency OAs with selectable gains of 10^5 V/A, 10^4 V/A, and 10^3 V/A in the frequency range from DC to 500 kHz, DC to 1.2 MHz, and DC to 2.4 MHz, respectively. The I/V converter has a low input impedance of the order of 0.1 Ω or less and is suitable for the wide range of applications in low temperature physics.

PRINCIPLE OF OPERATION

A schematic connection of the presented I/V converter is shown in Fig. 3. The differential pair of JFET transistors provides the high input differential impedance of the I/V converter, while two operational amplifiers serve as the active circuits stabilizing the working points of the JFET transistors in a broad frequency range up to a few MHz. The operational amplifier OA1 holds the bias voltage between the grounded gate and the source of the transistor T1 at constant value, which is equal to the value on its non-inverting input adjusted by the divider R1 and R2. This scheme offers a broad flexibility from the point of view of the working point adjustment for the various types of the input transistors and operational amplifiers. As the bias voltage of T1 is constant, the transistor T1 works like a current source supplying a constant current I_{DS1}. The current I_{DS1} generates constant voltage drop across the resistor R_{D1} and this voltage serves as the reference voltage for the second operational amplifier OA2.

OA2 drives the second transistor of the pair T2, working like an emitter follower, through the active negative feedback provided by the resistor R_F and capacitor C_F. This feedback sets the voltage drop on the resistor R_{D2} to be equal to that on R_{D1}, and because the gate of T1 is grounded, the gate of T2 is held by the feedback at the potential of the virtual ground. Now, let the input current of T2 go to zero. Then, the negative feedback of OA2 also sets its output voltage to be equal to zero (a voltage offset can be compensated by means of a compensation potentiometer). If the input current is nonzero, in order to keep the gate of T2 on the potential of the virtual ground, the active feedback of OA2 sets its output voltage to the value, at which the current flowing from the output through the resistor R_F equals to the value of the input current, i.e., $I_{in} \doteq -V_{out}/Z_F$.

In order to have a choice to select the amplification factor we added five reed relays controlled by a microcontroller

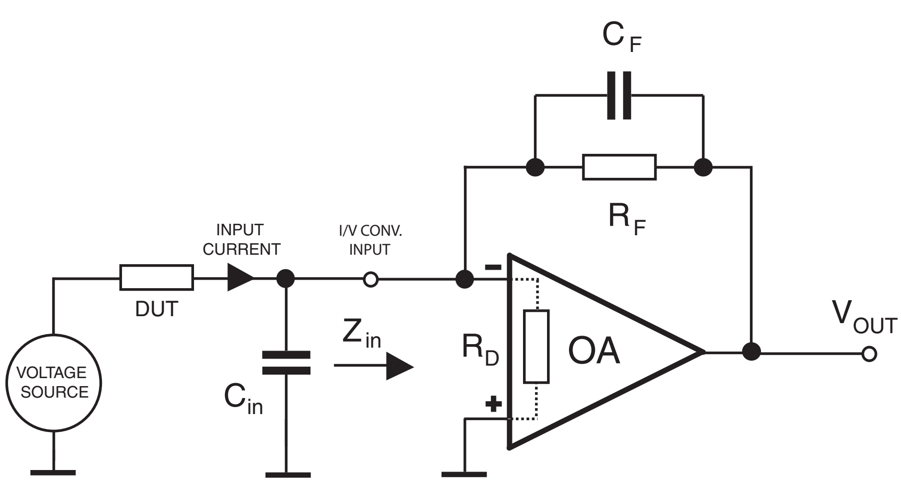

FIG. 2. The input impedance of the I/V converter Z_{in} with in parallel connected C_{in} and in series connected impedance of the device being measured (device under test, DUT) form a voltage divider of the excitation voltage source.

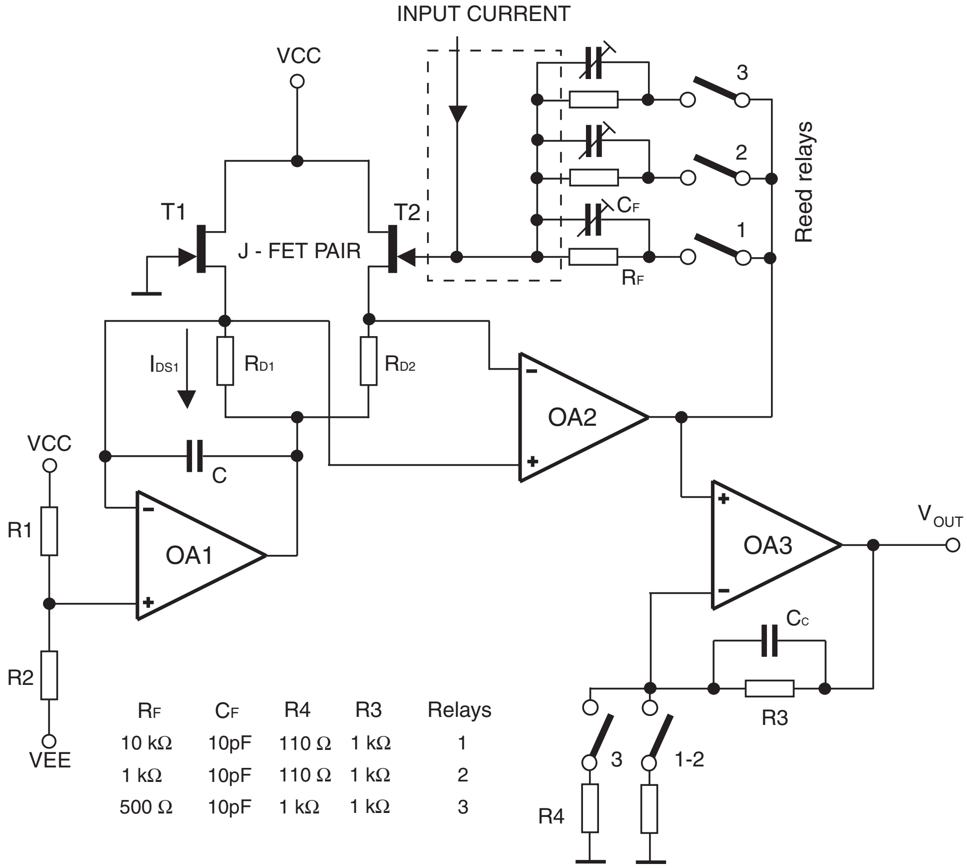

FIG. 3. Schematic connection of the I/V converter.

and darlington driver (Fig. 3 shows only their contacts). These contacts, as shown in Fig. 3, allow to connect one of the feedback impedances to the operational amplifier output providing the amplification factor and frequency response of the I/V converter. Finally, the third rf-operational amplifier works as a non-inverting amplifier and adds an additional amplification by the factor 10 or 2, which is dependent on the I/V gain selected.

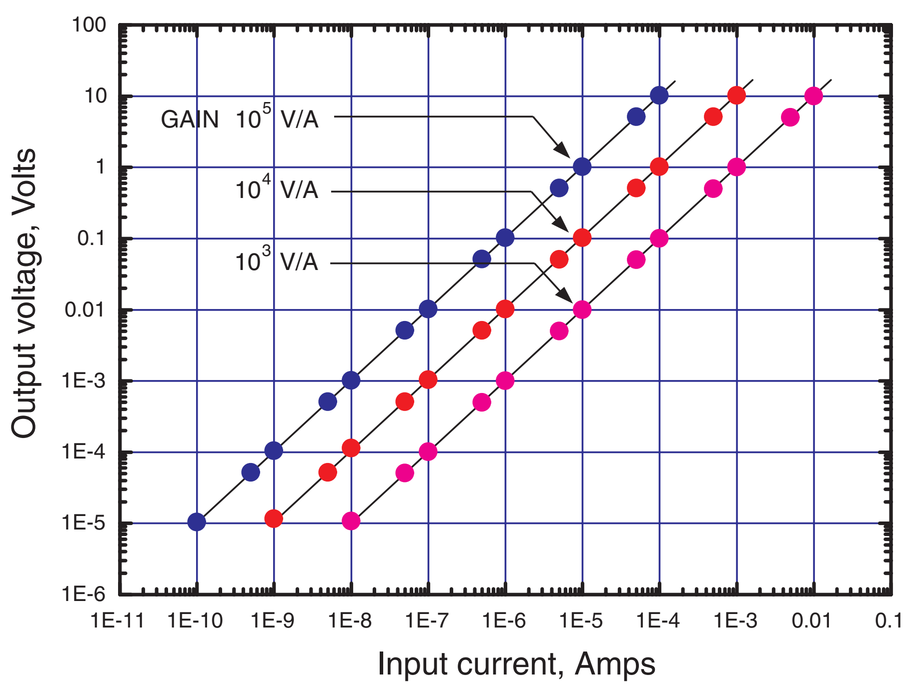

FIG. 4. DC characteristics of the I/V converter measured for three amplification factors 10^5 V/A, 10^4 V/A, and 10^3 V/A.

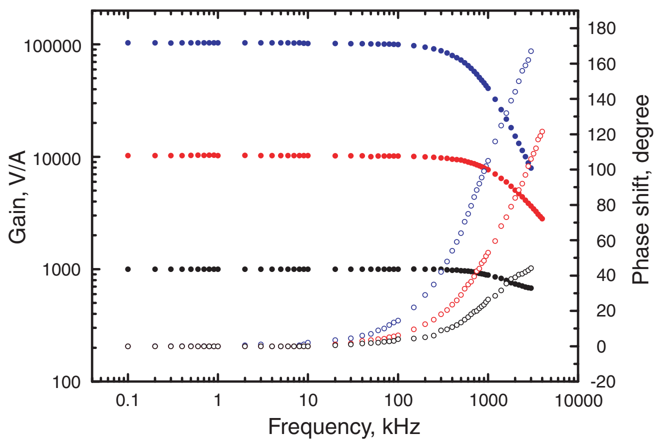

FIG. 5. The amplitude-frequency (solid points) and corresponding phase-frequency (open points, see scale on the right) characteristics of the current-to-voltage converter for three amplification factors.

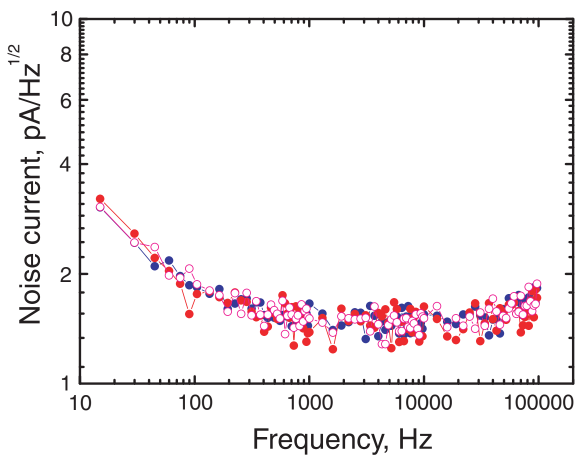

FIG. 6. Three noise spectral characteristics of the I/V converter measured at gain factor 10^5 V/A.

PROPERTIES OF THE I/V CONVERTER

Figure 4 presents the DC characteristics of the I/V converter, i.e., the dependence of the I/V converter output voltage measured for three amplification factors as a function of the DC input current. The Keithley Model 220 constant current source served as a source of the calibrated current and corresponding I/V converter output voltage were measured by a standard digital voltmeter (DVM). Slopes of the linear dependencies confirm the expected amplification factors of the I/V converter (10^3 V/A, 10^4 V/A, and 10^5 V/A). It is worth mentioning at this point that presented I/V converter covers the detection of the input current in the nine orders of magnitude.

The amplitude-frequency characteristics of the I/V converter are presented in Fig. 5. To measure these characteristics, a harmonic voltage generator was used as a signal source. The generator output voltage was attenuated by -40 dB attenuator. A resistor of the nominal value of 100 Ω connected between the attenuator and I/V converter input defined the current being detected by the I/V converter. One channel of a digital oscilloscope measured the I/V converter output voltage, while the second one simultaneously detected the generator output in order to measure the frequency and the phase characteristics of the converter. The small nominal value of 100 Ω of the input resistor and a short coaxial cable used for the connection (∼50 pF) minimized the signal phase shift on the input cable in the frequency range of interest and this phase shift was neglected. As follows from the Fig. 5, the frequency bandwidths of the I/V converter (defined as -3 dB attenuation) are 500 kHz, 1.2 MHz, and 2.4 MHz for gains 10^5 V/A, 10^4 V/A, and 10^3 V/A, respectively.

The corresponding phase-frequency characteristics are also shown in Fig. 5. The data shown in Fig. 5 are modified by subtracting the value of -180° from the originally measured data as mentioned above. As it can be seen from the scheme presented in Fig. 3, there are two contributions to the phase shift of the measured signal: the first one originates from the impedance Z_F and the second one is provided by the feedback impedance of non-inverting amplifier. Both of them can be controlled and adjusted by in parallel connected trimer (variable) capacitors (and resistors).

Figure 6 presents three independent measurements of the noise spectrum of the I/V converter at the gain factor of 10^5 V/A manifesting very good reproducibility. The region of $1/f$ noise can easily be distinguished from the region of the frequency independent Johnson (or thermal) noise. The latter is related to the thermal motion of electrons via feedback resistor R_F. Taking value of $R_F = 10^4\,\Omega$, the corresponding noise current I_T calculated from $\sqrt{4k_B T \Delta f / R_F}$ at room temperature T and bandwidth $\Delta f = 1$ Hz gives the value $I_T = 1.25$ pA. This is in very good agreement with measured values of the Johnson noise showed in Fig. 6, confirming that a main source of the thermal noise originates from R_F.

Finally we would like to make some remarks about technical realization of the I/V converter. In order to minimize input leakage currents, all input parts of the I/V converter (labeled by the dashed line in Fig. 3) are made and connected on a teflon insulator. The I/V converter we built has its own DC voltage power supply with DC voltage input (not shown in Fig. 3). This DC voltage input allows the I/V converter to be connected to the voltage outputs (usually) provided by commercial lock-in amplifiers. It makes the applications of the converter with lock-in amplifiers much easier. The I/V converter gain is selected using a none latching switch connected to microcontroller and darlington driver which controls the coils of the five reed relays.

CONCLUSIONS

We presented the principles of operation and technical characteristics of the I/V converter with a selectable gain. Its essential feature is its low input impedance of the order of 0.1 Ω and reasonable amplification of the order of 10^5 V/A in the frequency range up to 500 kHz. The I/V converter in combination with lock-in amplifier seems to be suitable for a wide range of applications such as detection of the piezoelectric transducers used in SPM techniques, the tuning forks, torsion oscillators, and various ultrasound transducers measurements in low temperature physics.

ACKNOWLEDGMENTS

Centre of Low Temperature Physics is operated as the Centre of Excellence CFNT MVEP of the Slovak Academy of Sciences. This work is supported by the grants: SF EU under contract ITMS 26220120005, APVV-432-07, APVV-515-10, VEGA 2/0128/12 (former VEGA 2/0025/09), EPSRC, and by Microkelvin, the project of 7. FP of EU. Support provided by the U.S. Steel Košice s.r.o. is also very appreciated.

[1] P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. (Cambridge University Press, 1989).
[2] K. Hayashi, K. Saitoh, Y. Shibayama, and K. Shirahama, J. Phys.: Conf. Ser. **150**, 012016 (2009).
[3] L. Libioulle, A. Radenovic, E. Bystrenová, and G. Dietler, Rev. Sci. Instrum. **74**, 1016 (2003).
[4] R. Blaauwgeers, M. Blažková, M. Človečko, V. B. Eltsov, R. de Graaf, J. Hosio, M. Krusius, D. Schmoranzer, W. Schoepe, L. Skrbek, P. Skyba, R. E. Solntsev, and D. E. Zmeev, J. Low Temp. Phys. **146**(5/6), 537 (2007).
[5] G. W. Morley, A. Casey, C. P. Lusher, B. Cowan, J. Saunders, and J. M. Parpia, J. Low Temp. Phys. **126**, 557 (2002).
[6] V. B. Efimov, D. Garg, M. Giltrow, P. V. E. McClintock, L. Skrbek, W. F. Vinen, J. Low Temp. Phys. **158**, 462 (2010).
[7] P. Skyba, J. Low Temp. Phys. **160**(5–6), 219 (2010).