Ultra-Low-Noise High-Input Impedance Amplifier for Low-Frequency Measurement Applications

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***Abstract*—The design of a low-frequency high-input-impedance amplifier having probably the lowest noise ever reported is presented. The amplifier's frequency range is from about 0.07 Hz to about 110 kHz at the −3-dB level. The equivalent input noise voltage spectral density is about 5.6, 1.4, 0.6, and 0.5 nV/$\sqrt{\text{Hz}}$ at frequencies 0.1, 1, 10, and 1000 Hz, respectively. Gain of the amplifier is about 83 dB. Noise analysis is made for active-type, capacitive-type, and low impedance signal sources. The contribution from different noise sources in the amplifier and JFET to the overall noise is shown.**

***Index Terms*—Amplifiers, analog circuits, impedance, JFETs, noise, noise measurement.**

I. INTRODUCTION

LOW-NOISE high-input-impedance amplifiers have been widely used in a variety of applications demanding measurement of small signals at low frequencies. Piezoelectric and seismic accelerometers, infrared detectors, optoelectronic devices, defect spectroscopy, measurements of small bioelectric signals, measurements related to reliability and diagnostic characterization of electronic devices and integrated circuits, and other applications (including the exotic gravitation waves reception) require the use of low-noise low-frequency measurement systems [1]–[16]. Noise floor of the whole measurement system is usually determined by the noise of input amplifier used in such a system. Design of a low-frequency ultra-low-noise amplifier (ULNA) is an attractive goal for many applications, but it is a challenging task at the same time.

Amplifier's noise depends mainly on the noise of its first stage (preamplifier) if the noise of other stages is made negligible compared with the preamplifier's noise. Designers of the low-noise amplifiers try to decrease noise contribution from all other noise sources (for example, power supply noise or environmental noise). As a result of those efforts, they can provide a condition that the noise floor of the amplifier is determined mainly by the noise of an electronic device used in the preamplifier. It is not an easy task because the noise of the electronic devices has decreased significantly.

JFET or MOSFET are two kinds of active devises providing high input impedance (more then about 10^5 Ω) in an amplifier. When signal source impedance is small (less than about 10^4 Ω), BJT is commonly used in a preamplifier. High input impedance of an amplifier, contrary to low input impedance, allows working with a signal source having either high or low impedance. Typically, JFETs have about the same or lower noise than BJTs, and both of them have much lower noise than any MOSFETs [2], [3], [10], [17], and [18]. So, only JFETs are appropriate for high-input-impedance ULNA.

It is known that low-frequency noise, so called $1/f$ noise, is present in many electronic devices. It defines the principal threshold of the small signal measurements at low frequencies and determines the phase noise of oscillators through the up-conversion process [19]–[23]. Also, low-frequency noise can serve as a very sensitive measure of defects in semiconductor devices, integrated circuits, VLSI circuits, materials, and their quality and reliability [7]–[10]. For example, spectral analysis of resistance fluctuations in metallization lines allows investigating electromigration, one of the most frequent causes for VLSI circuit's failure [9], [10]. Therefore, reducing noise floor of the measurement system's amplifier allows measuring small low-frequency signals (for example, vibration or seismic signals measured by a piezoelectric accelerometer). On the other hand, it allows investigation of small defects in semiconductor devices, circuits, and materials.

There is extensive literature about low-noise high-input-impedance amplifiers comprising low-noise JFETs [1]–[4], [14], [25]–[34]. Designers of these amplifiers have tried to reduce their noise floor as much as possible. However, only a few of them can be classified as true low-frequency ULNA. Particularly, the low-frequency high-input-impedance ULNA was described in the paper [1] published in 1991. That ULNA had probably the lowest noise values for high impedance amplifiers ever reported to date. The ULNA presented in the current paper has equivalent input noise voltage spectral density e_n 2–3 times less at frequencies $0.1\text{ Hz} \leq f \leq 1\text{ Hz}$ and about the same at frequencies $f \geq 100$ Hz compared with the amplifier described in [1].

This paper describes an ULNA design based on previous work of the author on low-noise JFET amplifiers [3], [17], and [25]. This ULNA has some features in common with the amplifiers described previously. For example, for low-impedance and active-type signal source, low-noise characteristics of both the ULNA presented here and the amplifier described in [25] are mainly determined by the noise of the chosen preamplifier's JFET. However, [25] didn't show how this was achieved. Low-noise and low-frequency electronics designers know how important and, at the same time, how difficult it is to make the contribution of all noise sources small enough compared with the input JFET noise, especially when this noise is estimated at a few nV/$\sqrt{\text{Hz}}$ at frequencies $f \leq 1$ Hz and less than 1 nV/$\sqrt{\text{Hz}}$ at frequencies $f > 1$ Hz. The schematic

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solution of the preamplifier and the other stages of an amplifier (major amplifier) play a critical role in this accomplishment. In addition, the major amplifier of an ULNA determines the important parameters, such as gain, frequency response, input capacitance, and output impedance. [25] revealed the JFET preamplifier's schematic only and just briefly described the major amplifier. The following information shows the significant differences and the new results obtained by the author in comparison to his previous work.

1) The designed high input impedance ULNA features the lowest noise ever reported at the frequency range from 0.1 Hz to 100 kHz. Complete and detailed schematic of the ULNA, including all of its stages, basic parameters, theoretical noise analysis, and the noise measurement results are described for the first time. This ULNA is designed and optimized from the standpoint of providing the lowest possible noise at the frequency range mentioned above.
2) The preamplifier used in the system described in [25] is designed for the JFET's $1/f$ and channel thermal noise measurement. Therefore, it operates always with the short circuit at its input. This case corresponds to the dc-coupling with the active-type signal source, having output resistance $R_s = 0$. The amplifier can not operate with the capacitance-type signal source because biasing of the JFET is provided through the signal source resistance. Also this amplifier can not operate if the signal source contains dc voltage. The new preamplifier comprises an input $R - C$ circuit, which provides ac coupling of the ULNA input to the signal source. As a result, the ULNA can operate with either an active- or capacitance-type signal source, or either with a high- or low-impedance signal source. Also, the signal source could have dc voltage. The frequency band of the designed ULNA is widened from 0.5 Hz to 0.1 Hz at low frequencies and from 50 kHz to 100 kHz at high frequencies compared with the ULNA described in [23].
3) It is shown how the major amplifier allows of reducing the input capacitance of the ULNA caused by the Miller effect.
4) The current paper contains detailed noise analysis of the designed ULNA. It comprises a complete equivalent noise circuit including ULNA input capacitance. The noise analysis takes into account the noise created by the circuit mentioned above and the noise created by the $R-C$ circuit between the JFET source and the circuit ground. Formulae for the equivalent input noise voltage spectral density referred to the signal source terminals are obtained for active-type, capacitive-type, and low impedance signal sources. Contribution from different noise sources of the amplifier and JFET is shown at different frequencies from 0.1 Hz to 100 kHz.
5) The previous papers [3], [17] described mainly the noise analysis of the system signal source—JFET amplifier in the common case. The JFET amplifier was shown symbolically, without schematic details. The JFET amplifier examples presented in those papers have a frequency range restricted at low end $(f \geq 1\ \text{Hz})$. Besides, their noise is about two orders of magnitude higher at frequencies $f \leq 100$ Hz and about one order of magnitude higher at frequencies $f \geq 1$ kHz compared to the noise of the ULNA achieved in the present work.
6) The preamplifier of the current ULNA, unlike the similar stage presented in [3] and [17], includes the $R - C$ circuit between the JFET source and the circuit ground. As it's shown below, this circuit plays a critical role in determining important parameters of the ULNA, such as noise, gain, and frequency response.
7) For the first time, noise comparison of two types of JFETs having the lowest noise to date, IF9030, produced by InterFET Corp., and 2SK369, produced by Toshiba Corp. is shown at the wide frequency range from 0.1 Hz to 50 kHz.

II. ULNA Design

A. Choice of JFET

Below, it will be shown that for the low impedance signal source, noise floor of the ULNA is determined mainly by the noise of the JFET chosen for its preamplifier. Therefore, first of all, it's needed to choose JFET having the lowest $1/f$ and channel thermal noise possible.

Thanks to the great progress in fabrication technology process, $1/f$ noise of modern low-noise JFETs has decreased significantly. In addition, the frequency range of this noise has shifted to the lower frequencies. There are some modern n-channel JFETs which can be used as possible candidates for the ULNA [25]–[28]. Unfortunately, actual values of their low-frequency noise are shown inadequately in the literature. Usually, data sheets show the value of the equivalent input noise voltage density e_n or noise figure NF at one frequency $f = 1$ kHz, or 100 Hz. These frequencies are out of the $1/f$ noise frequency range. Some data sheets contain the plots e_n or NF versus f, but these plots have very restricted frequency range, usually $f \geq 10$ Hz, very seldom $f \geq 1$ Hz. Those values of noise do not correspond to the actual level of noise, which can vary from sample to sample and supplier to supplier for the same type of JFET. No vendors of JFETs consider $1/f$ noise measurement, because they don't wish to spend precious and costly time measuring $1/f$ noise. Besides, they do not have enough low-noise instruments capable of measuring JFETs noise at low-frequencies. The type and samples of JFET for the ULNA presented in the current paper were chosen based on the noise measurement of different modern low-noise JFETs at low frequencies. This measurement was made with help of the system designed for experimental investigation of low-frequency noise of JFETs [25]. Thus, it made possible to choose the type and samples of JFET with the lowest noise at present that is critical for the design of the ULNA described below.

There are probably only two groups of low-noise n-channel silicon JFETs which can serve as possible candidates for that amplifier at present. One group contains JFETs IF9030, or IF1801, or IF3601 produced by InterFET Corp. They have about the same value of e_n among that group [25], [26]. Another group contains JFETs 2SK369, 2SK146, or 2SK371 produced by Toshiba Corp. They also have about the same value of e_n among that group [1], [27], [28]. The e_n measurements of 10 samples of JFETs IF9030 and 10 samples of JFETs 2SK369

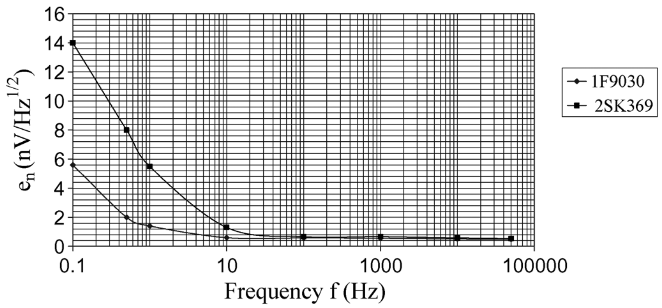

Fig. 1. Equivalent input noise voltage spectral density e_n of the best samples of the measured JFETs IF9030 and 2SK369.

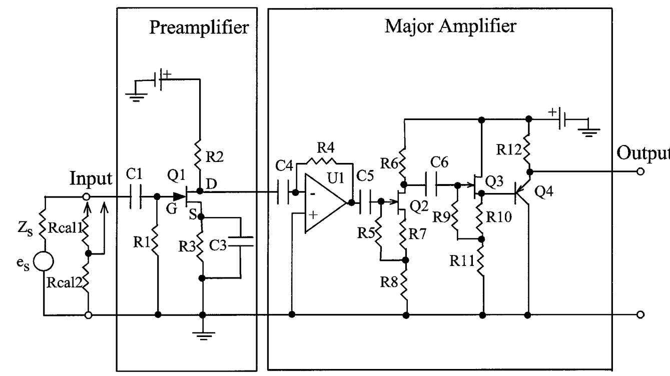

Fig. 2. Schematic of the designed ULNA.

were made at a frequency range from 0.1 Hz to 50 kHz with the help of the low-noise measurement system presented in [25]. Frequency range of that system was extended in the low frequency from 0.5 Hz to 0.1 Hz by increasing value of the capacitor bypassing the JFET source resistor. Measurement results for the best samples from measured JFETs are shown in Fig. 1. Noise of 2SK369 is determined mainly by its $1/f$ noise at frequencies $f \leq 10$ Hz and by its channel thermal noise at frequencies $f \geq 100$ Hz. At frequencies $10 \leq f \leq 100$ Hz both of those noise sources of JFET should be taken into account. For the IF9030 $1/f$ noise prevails over its channel thermal noise at frequencies $f \leq 2$ Hz. At frequencies $f \geq 10$ Hz its channel thermal noise is a main source of noise. At frequencies $2 \leq f \leq 10$ Hz both of those noise sources have comparable values. The e_n values of the best sample from the investigated JFETs IF9030 were 5.6, 1.4, 0.6, and 0.5 $\text{nV}/\sqrt{\text{Hz}}$ at frequencies 0.1, 1, 10, and 1000 Hz, respectively. The e_n values of the best sample from the investigated JFETs 2SK369 were 14, 5.5, 1.3, and 0.7 $\text{nV}/\sqrt{\text{Hz}}$ at the same frequencies 0.1, 1, 10, and 1000 Hz, respectively. Those noise measurements were made at the drain current I_D of about 5 mA and drain–source voltage V_{DS} between 3 and 4 Vdc for both types of JFETs. Among the 10 samples, noise value deviations between the best and the worst samples were not more than 2 times for each of those groups of JFETs. The IF9030 had e_n values less than the 2SK369 by a factor of 2.5–4.0 at frequencies 0.1 Hz $\leq f \leq$ 1 Hz and by a factor of about 2 at frequency 10 Hz. Both groups had about the same e_n values at frequencies f $\geq$ 100 Hz. It is expected that at frequencies below 0.1 Hz the noise of IF9030 is less than the noise of 2SK369 by a factor of $\geq$4. The current noise source of those JFETs, i. e. shot noise current i_n, which is defined by the gate leakage current I_{GSS}, is about the same for those two groups of JFETs because they have about the same value of I_{GSS}.

B. Schematic of the Designed ULNA

Schematic solution of the ULNA is made from the standpoint of providing as little noise as possible. The circuit diagram of the designed amplifier is shown in Fig. 2. It comprises five ac-coupled stages. The first stage is a common-source JFET preamplifier with the active device $Q1$, JFET IF9030, sorted on the best level of e_n. The other four stages form the major amplifier. In Fig. 2, e_s and Z_s are the signal source's electromotive force (EMF) and the signal source impedance, respectively. The basic destination of the input ac-coupled circuit $R1-C1$ is to provide the possibility for ULNA to operate either with an active or capacitive type signal source. Also, the signal source could have either low or high impedance. Resistor $R1$ supplies a path for gate leakage current of $Q1$. The value of $R1$ determines the amplifier's input resistance R_{in} which equals 300 MΩ. Resistors $R1$ and $R3$ provide bias for $Q1$: the dc voltage drop across $R3$ creates reverse voltage gate-source V_{GS} applied between the $Q1$ gate and the source through $R1$. The values of resistors $R2$ and $R3$ are chosen to provide drain current $I_D \approx 5$ mA. Capacitor $C1$ also works as a decoupling capacitor between the input of JFET and the dc voltage possibly presented in the signal source. $R1$ and $C1$ create the input high-pass filter for the measured signal. The value of $C1$ is chosen high enough $(C1 = 68\ \mu\text{F})$ to provide flat frequency response and negligible contribution of the $R1$ thermal noise at the amplifier's frequency band. High input filter time constant requires significant time to charge $C1$ (if the signal source contains dc voltage), which, in turn, leads to a long settling time. A fast recovery can be acquired by connecting the right side of $C1$ to the circuit ground for about 1 min before any measurements are taken. Capacitor $C3$ is used to increase gain G_1 of the preamplifier so that the following condition takes place:

$$e_{n1} \cdot G_1 \gg e_{nM} \tag{1}$$

where e_{n1} and e_{nM} are equivalent input noise voltages of the preamplifier and the major amplifier, respectively. Condition (1) practically eliminates the influence of the major amplifier's noise on the total amplifier's noise. Schematic solution of the major amplifier, e. g., choice of low-noise $U1$, $Q2$, and $Q3$, also contributes to this condition. Another destination of $C3$ is to decrease the thermal noise created by $R3$ and the shot noise created by I_D flowing through $R3$ at the amplifier's frequency band. Value of $C3$ is chosen high enough $(C3 = 0.18\ \text{F})$, to achieve condition (1). More detailed noise analysis of the designed amplifier is shown below.

The major amplifier's first stage is based on the opamp OPA27 produced by Texas Instruments. The use of an opamp allows reducing the input capacitance C_{in} of the preamplifier

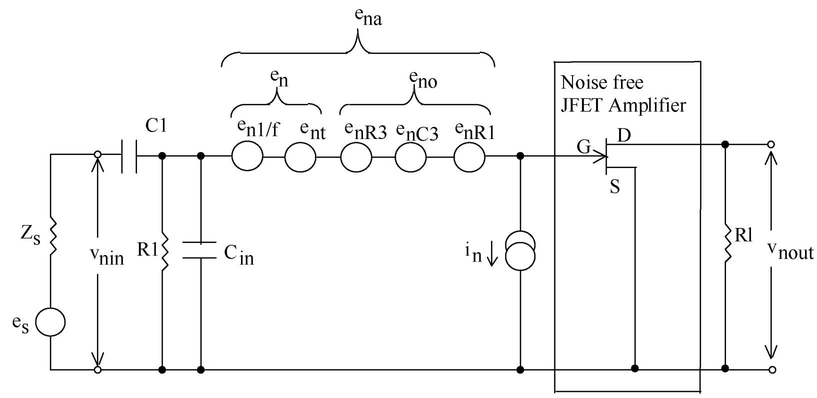

Fig. 3. Equivalent noise circuit of the designed ULNA.

and correspondingly $C_{\rm in}$ of the whole amplifier. Indeed, expression for $C_{\rm in}$ of the common-source FET amplifier without load is the following [32]:

$$C_{\rm in} = C_{gs} + C_{gd}(1 - G_1) \tag{2}$$

where C_{gs} and C_{gd} are the gate-source and gate-drain capacitances of $Q1$, respectively. The second item in (2) reflects the magnification factor for C_{gd} caused by the Miller effect. For the same amplifier loaded to opamp, $C_{\rm in}$ becomes

$$C_{\rm in} = C_{gs} + C_{gd} \tag{3}$$

since the inverting input of opamp provides the virtual ground. Therefore, the Miller effect is eliminated for the capacitance C_{gd}. The measured value of $C_{\rm in}$ is about 160 pF. The major amplifier's second stage is a common-source amplifier based on JFET 2N4338. The third stage of the major amplifier is a source follower based on JFET 2N4338. The fourth stage is an emitter follower based on BJT 2N3906, which provides low output impedance, $R_{\rm out} \leq 100\ \Omega$. The measured gain of the preamplifier was $G_1 = 45.2$ dB at frequency 1 kHz. Gain of the major amplifier was $G_2 = 37.8$ dB at the same frequency. Total gain of the ULNA was $G = G_1 G_2 = 83$ dB $\pm\, 0.5$ dB at frequency 1 kHz. Deviation in gain is caused mainly by variations in the transconductance g_{fs} of the used JFETs. Gain can be adjusted by change of resistor $R8$. Frequency response of the complete ULNA is from 0.07 Hz to 110 kHz at the level -3 dB. The lower corner of the preamplifier's frequency response is basically determined by the value of the time constant $\tau_3 = R3 \cdot C3$. For the designed amplifier, capacitor $C3$ is comprised of the combination of three miniature aluminum electrolytic capacitors of VK type, produced by Nichicon, with a total value of about 0.18 F. This value of $C3$ in combination with value of $R3 = 88.7\,\Omega$ provides the lower corner (-3 dB) of the ULNA about 0.07 Hz. The accuracy of $C3$ value is important to establish the lower corner of the frequency range. $C3$ had tolerance $\pm 20\%$. The upper corner of the frequency response is restricted mainly by the major amplifier's maximum frequency of stable amplification. Gain of the ULNA can be calibrated each time, before or after the noise measurement, by applying a signal from a signal generator to the input of the amplifier through the resistive voltage divider $Rcal1 - Rcal2$, which has a transfer coefficient of 0.1. In order to reduce the influence of environmental noise and thermal fluctuations of $C3$, the preamplifier with major amplifier and capacitor $C3$ were enclosed separately in two shielding metal cases with good temperature isolation between those cases. Rechargeable batteries were used as power supplies for the ULNA.

C. Equivalent Noise Circuit of the Designed ULNA

The ULNA's equivalent noise circuit is shown in Fig. 3. In Fig. 3, e_s is a signal source's EMF, Z_s is its output impedance, and $C_{\rm in}$ is the preamplifier's input capacitance. Noise generated within the preamplifier is represented by two noise generators at its input, e_{na} and i_n. e_{na} is the equivalent total preamplifier's input noise voltage spectral density generator. i_n is the input noise current spectral density generator [33]. Those noise generators can be found in principle to be partially correlated, but in practice, their correlation is close to zero [33], [34]. In this equivalent circuit, it is assumed that the JFET amplifier is an ideal noise-free amplifier. The total noise voltage of the preamplifier e_{na} is composed of the noise voltage of JFET e_n and the other noise voltage sources e_{no} uncorrelated to each other [25]

$$\begin{aligned} \overline{e_{na}^2} &= \overline{e_n^2} + \overline{e_{no}^2}, \quad \overline{e_n^2} = \overline{e_{n1/f}^2} + \overline{e_{nt}^2},\\ \overline{e_{no}^2} &= \overline{e_{nR3}^2} + \overline{e_{nC3}^2} + \overline{e_{nR1}^2}. \end{aligned} \tag{4}$$

In (4), $e_{n1/f}$ is the JFET $1/f$ noise, which usually predominates over other JFET noise sources at low frequencies. e_{n_t} is the JFET channel thermal noise caused by the thermal fluctuations among the channel's current carriers. e_{nR3} is the noise created by a combination of the thermal noise of $R3$ e_{nR3t} and the noise e_{nR3s} caused by the shot noise current i_s flowing through the circuit $R3 - C3$

$$\overline{e_{nR3}^2} = \overline{e_{nR3t}^2} + \overline{e_{nR3s}^2}. \tag{5}$$

In its turn, i_s is created by the channel current I_D flowing through R3. e_{nC3} is the noise of capacitor $C3$ determined by its dissipation factor (loss factor) [25], [35], [36]. e_{nR1} is the thermal noise of the resistor $R1$. The noise current generator i_n is determined by the shot noise current in the gate circuit caused by the JFET's gate leakage current I_G. We disregarded one more noise source of JFET, namely, induced gate current noise because, in practice, it is negligible compared with other JFET's noise sources [33], [34].

Our goal is to find the ULNA's overall equivalent noise voltage spectral density v_{ns} referred to the signal source terminals

$$\overline{v_{ns}^2} = \overline{v_{nin}^2} \cdot \left|\frac{1}{Z_1}\right|^2$$
$$Z_1 = \frac{R1}{Z_s(1 + j\omega R1C_{\text{in}}) + R1 + \frac{1}{j\omega C1}}. \quad (6)$$

In (6), v_{nin} is the noise referred to the JFET input, Z_1 is the transfer coefficient of the input circuit, ω is the angular frequency in radians/second, $\omega = 2\pi f$. v_{nin} can be expressed as

$$\overline{v_{nin}^2} = \overline{e_{na}^2} + \overline{v_{ni}^2}, \quad \overline{v_{ni}^2} = \overline{i_n^2} \cdot |Z_2|^2,$$
$$Z_2 = \left[R1 \middle\| \left(Z_s + \frac{1}{j\omega C1}\right) \middle\| \frac{1}{j\omega C_{\text{in}}}\right]$$
$$= \frac{R1(1+j\omega C1Z_s)}{1+j\omega C1(R1+Z_s)+j\omega R1C_{\text{in}}(1+j\omega C1Z_s)}. \quad (7)$$

In (7), v_{ni} is the noise voltage created by noise current i_n. To obtain v_{nin} according to (7), first, one must find each of the noise voltage sources in terms of the noise voltage spectral density contained in (4). Fig. 1 shows the values of the noise voltage $e_{n1/f}$ and e_{nt} of JFET IF9030 measured with help of the low-noise measurement system described in [25].

e_{nR3} can be obtained with (5) by finding e_{nR3t} and e_{nR3s}. e_{nR3t} is determined by the thermal noise of resistor $R3$

$$\overline{e_{nR3t}^2} = \frac{4kTR3}{1 + (\omega R3C3)^2}. \quad (8)$$

In (8), k is the Boltzmann's constant; T is the absolute temperature in Kelvin. Since

$$(\omega R3C3)^2 \gg 1 \quad (9)$$

at all measured frequencies from 0.1 Hz to 110 kHz, (8) can be rewritten as

$$\overline{e_{nR3t}^2} = \frac{4kT}{R3(\omega C3)^2}. \quad (10)$$

From (10), we can see that the contribution of e_{nR3t} into the overall noise is negligible at all frequencies from 0.1 Hz to 110 kHz. Indeed, for example, at frequency 0.1 Hz with $R3$ and $C3$ values discussed above we can obtain $e_{nR3t} \approx 0.04\ \text{nV}/\sqrt{\text{Hz}}$.

e_{nR3s}, created by the shot noise current i_s flowing through circuit $R3 - C3$, has the following relationship:

$$\overline{e_{nR3s}^2} = \overline{i_s^2} \cdot |Z_3|^2 = 2qI_D \cdot |Z_3|^2,$$
$$|Z_3|^2 = \frac{R3^2}{1 + (\omega R3C3)^2} \approx \frac{1}{(\omega C3)^2}. \quad (11)$$

In (11), q is the electron charge. Estimation of e_{nR3s}, according to (11), at $I_D = 5$ mA gives us the value of $e_{nR3s} \approx 0.07\ \text{nV}/\sqrt{\text{Hz}}$ at frequency 0.1 Hz. That estimation also shows that contribution of e_{nR3s} into the overall noise is negligible at the measured frequency range.

The noise voltage e_{nC3}, created by the electrolytic capacitor $C3$, having a dissipation factor η, is determined by the following expression [36]:

$$\overline{e_{nC3}^2} = \frac{4kT}{\omega C3\left(\eta + \frac{1}{\eta}\right)}. \quad (12)$$

The value of η measured by the HP 4284A Precision LCR Meter was $\eta \approx 0.4$ at frequency 20 Hz. Then according to (12) and supposing that η is constant at all frequencies, we can get $e_{nC3} \approx 0.2\ \text{nV}/\sqrt{\text{Hz}}$ at frequency 0.1 Hz that is much less than the noise $e_{n1/f}$ of JFET at the same frequency. The parasitic resistance R_P of $C3$ related to its leakage current has little influence on the overall noise of the preamplifier. This is because R_P is connected in parallel with $R3$ and $R_P \gg R3$, which is less than 100 Ω. The measured value of R_P was about 8 kΩ. One can expect the electrolytic capacitors ($C3$) to have high level of low-frequency fluctuations in the electrolyte at thermal variations. In order to reduce those fluctuations, as it was mentioned above, the preamplifier with major amplifier and capacitor $C3$ were enclosed separately in two shielding metal cases with good temperature isolation between those cases. Noise measurements didn't uncover any influence of those fluctuations on the results.

Noise e_{nR1} created by the thermal noise of resistor $R1$ can be obtained from the following expression:

$$\overline{e_{nR1}^2} = \frac{4kTR1}{1 + (\omega R1C1)^2}. \quad (13)$$

In (13), we assumed that $Z_s = R_s = 0$ and $C1 \gg C_{\text{in}}$. Since $(\omega R1C1)^2 \gg 1$ at the measured frequency range, (13) transforms into

$$\overline{e_{nR1}^2} = \frac{4kT}{R1(\omega C1)^2}. \quad (14)$$

From (14), we can see that the noise e_{nR1} is much less than the JFET noise $e_{n1/f}$ and e_{nt} at all measured frequencies. For example, $e_{nR1} \approx 0.004\ \text{nV}/\sqrt{\text{Hz}}$ at frequency 0.1 Hz.

Now we will find the second term of expression (7), noise voltage v_{ni} determined by the noise current spectral density i_n. When using the active-type signal source, $Z_s = R_s$ and assuming that, practically, $R_s \ll R1$, $(\omega R1C1)^2 \gg 1$ at all amplifier's frequency band, expression (7) for v_{ni} can be rewritten as

$$\overline{v_{ni}^2} = \overline{i_n^2} \cdot \left\{\frac{1}{1 + (\omega R_s C_{\text{in}})^2} \cdot \left[R_s^2 + \frac{1}{(\omega C1)^2}\right]\right\}. \quad (15)$$

For a low-impedance signal source, assuming that $(\omega R_s C_{\rm in})^2 \ll 1$ at all frequency band, expression (15) transforms into

$$\overline{v_{ni}^2} = \overline{i_n^2} \cdot \left[R_s^2 + \frac{1}{(\omega C1)^2} \right]. \tag{16}$$

If we have a capacitance-type signal source, $Z_s = (1/j\omega C_s)$ and we assume that, practically always, $C_s \ll C1$, v_{ni} in (7) and e_{nR1} in (13) can be rewritten as

$$\overline{v_{ni}^2} = \overline{i_n^2} \cdot \frac{R1^2}{1 + [\omega R1(C_s + C_{\rm in})]^2}, \tag{17}$$

$$\overline{e_{nR1}^2} = \frac{4kTR1}{1 + [\omega R1(C_s + C_{\rm in})]^2}. \tag{18}$$

From (15)–(17) we can see that the noise v_{ni} depends on the values of i_n of JFET, the value of source impedance (R_s or C_s), capacitor $C1$, and the input capacitance $C_{\rm in}$. i_n is the shot noise caused by the leakage current I_G in the gate circuit of JFET [33], [34]

$$\overline{i_n^2} = 2qI_G. \tag{19}$$

For JFET IF9030 $I_G \leq 10^{-10}$ A [26] and correspondingly $i_n \leq 6 \cdot 10^{-15}$ A/$\sqrt{\rm Hz}$ in accordance with (19). With such value of i_n, the contribution of v_{ni} into the overall noise is practically negligible compared with e_n, for a low impedance signal source. For example, if $Z_s = R_s \leq 100$ kΩ, then according to (16), noise voltage $v_{ni} \leq 0.6$ nV/$\sqrt{\rm Hz}$ at the lowest measured frequency 0.1 Hz. If $Z_s = 1/j\omega C_s$ then, according to (17) and (18), we need to take into account the noise v_{ni} and e_{nR1} at low frequencies for small values of C_s.

As a result of noise analysis made above, expressions (6) and (7) can be rewritten for an active-type signal source, as

$$\overline{v_{ns}^2} = \left[1 + (\omega R_s C_{\rm in})^2\right] \cdot \overline{v_{nin}^2} \tag{20}$$

and

$$\overline{v_{nin}^2} = \overline{e_{n1/f}^2} + \overline{e_{nt}^2} + \overline{i_n^2} \cdot \left\{ \frac{1}{1 + (\omega R_s C_{\rm in})^2} \cdot \left[R_s^2 + \frac{1}{(\omega C1)^2} \right] \right\}. \tag{21}$$

The first two terms in (21) are the $1/f$ and channel thermal noise of JFET, respectively. The third term represents the shot noise in the gate circuit. For a capacitive-type signal source, (6) and (7) become:

$$\overline{v_{ns}^2} = \left(1 + \frac{C_{\rm in}}{C_s}\right)^2 \cdot \overline{v_{nin}^2} \tag{22}$$

and

$$\overline{v_{nin}^2} = \overline{e_{n1/f}^2} + \overline{e_{nt}^2} + \frac{4kTR1}{1 + [\omega R1(C_s + C_{\rm in})]^2} + \overline{i_n^2} \cdot \frac{R1^2}{1 + [\omega R1(C_s + C_{\rm in})]^2}. \tag{23}$$

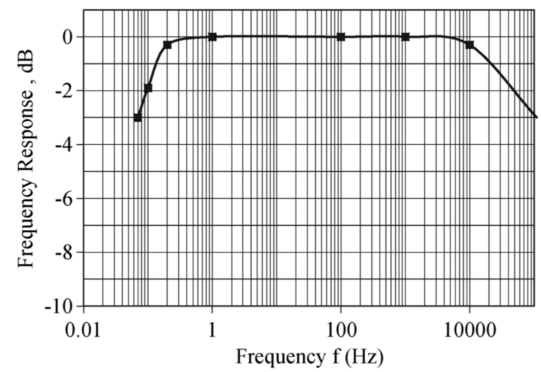

Fig. 4. Frequency response of the designed ULNA.

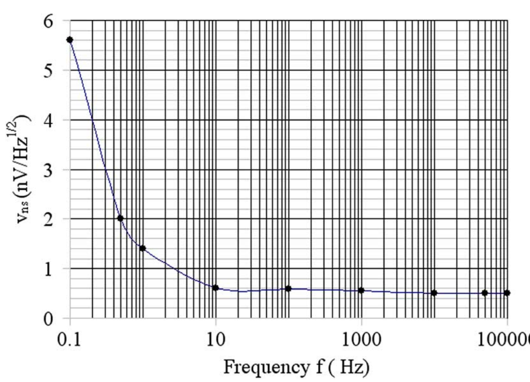

Fig. 5. The designed ULNA's equivalent input noise voltage spectral density $v_{\rm ns}$ referred to the signal source terminals.

In (23), the first two terms are the JFET's $1/f$ and channel noise, respectively, the third term is the thermal noise caused by resistor $R1$, and the last represents the shot noise in the gate circuit. For the low-impedance signal source, expressions (20)–(23) transform into:

$$\overline{v_{ns}^2} = \overline{v_{nin}^2} = \overline{e_{n1/f}^2} + \overline{e_{nt}^2}. \tag{24}$$

So, the overall noise of the designed ULNA for a low-impedance signal source is determined mainly by the two noise sources of JFET, $e_{n1/f}$ and e_{nt}. For a high-impedance signal source, it's needed, also, to take into account the shot noise current i_n in the JFET gate circuit and the thermal noise e_{nR1} of the JFET biasing resistor $R1$.

III. Measurement Results

The designed ULNA's equivalent input noise voltage spectral density v_{ns}, referred to the signal source terminals, has been measured at $Z_s = R_s = 0$ (the short circuit at the ULNA input) at frequency band from 0.1 Hz to 100 kHz and at room temperature. In this measurement, v_{ns} was defined as $v_{ns} = v_{\rm nout}/G$, where v_{nout} is the noise voltage spectral density measured at the output of the amplifier and G is its gain measured at a particular frequency. v_{nout} was measured by a Hewlett Packard 3562A Dynamic Analyzer. Fig. 4 and Fig. 5 show the measured frequency response and noise voltage v_{ns}, respectively. Frequency response was from 0.07 Hz to 110 kHz at level −3 dB. Gain of the ULNA was 83 dB ± 0.5 dB at frequency 1 kHz. v_{ns} of the amplifier was 5.6 nV/$\sqrt{\text{Hz}}$ at frequency 0.1 Hz, 1.4 nV/$\sqrt{\text{Hz}}$ at frequency 1 Hz, 0.6 nV/$\sqrt{\text{Hz}}$ at frequency 10 Hz, and 0.5 nV/$\sqrt{\text{Hz}}$ at frequencies from 1 kHz to 100 kHz. At frequencies f $\leq$ 2 Hz, the amplifier's overall noise is determined mainly by the JFET's $1/f$ noise. At frequencies $f \geq 10$ Hz, the JFET's channel thermal noise predominates over other noise sources of the amplifier. At frequencies from 2 Hz to 10 Hz, both those noise sources should be taken into account. The ULNA and the used JFET practically don't exhibit $1/f$ noise at frequencies $f \geq 10$ Hz. Those noise measurement results have good correlation with the noise theoretical analysis made above.

Noise of JFET can be varying dependently on its operation conditions, basically on values of I_D and V_{DS}. For the same sample of IF9030, this noise was measured at $I_D \approx 5$ mA and $I_D \approx 300$ μA. $1/f$ noise was about the same at those values of I_D. The thermal channel noise increased about two times when I_D decreased from 5 mA to 300 μA. The same results were obtained in [25]. Usually, $1/f$ noise increases with the V_{DS} increase. More detailed dependence of JFET noise versus variations in V_{DS} requires further investigations. In the designed ULNA, $I_D \approx 5$ mA and $V_{DS} \approx 3$ V. Those values are kept for each sample of the JFET by adjustment of the resistors $R2$ and $R3$.

The ULNA's input resistance R_{in}, input capacitance C_{in}, and the settling time T_s were also measured. T_s is the time elapsed from the moment of power-on to the moment when it is possible to begin a measurement of noise and other parameters of the amplifier. The measured values of R_{in}, C_{in}, and T_s were: $R_{\text{in}} \approx 300$ MΩ, $C_{\text{in}} \approx 160$ pF, and $T_s \approx 10$ minutes, respectively. The designed high-input-impedance ULNA has about 2–3 times less noise at frequencies from 0.1 to 1 Hz and about the same noise at frequencies $\geq$100 Hz, compared with the noise of the preexistent ULNA described in [1], which was probably the best high-input-impedance amplifier in respect of low noise to date.

IV. Conclusion

An ultra-low-noise high-input-impedance low-frequency amplifier, having probably the lowest noise ever reported to date, is designed and tested. The amplifier's frequency range is from about 0.07 Hz to about 110 kHz at the -3-dB level. The equivalent input noise voltage spectral density is about 5.6, 1.4, 0.6, and 0.5 nV/$\sqrt{\text{Hz}}$ at frequencies 0.1, 1, 10, and 1000 Hz, respectively. Gain of the amplifier is 83 dB $\pm$ 0.5 dB at frequency 1 kHz. Input impedance is about 300 MΩ and the input capacitance is about 160 pF. The amplifier's noise measurements results have good correlation with the theoretical noise analysis. Formulae for the equivalent input noise voltage spectral density referred to the signal source terminals are obtained for active-type, capacitive-type, and low-impedance signal sources. For a low-impedance signal source, the overall noise of the amplifier is determined mainly by the $1/f$ noise of the input JFET at frequencies $f \leq 2$ Hz and by the JFET channel thermal noise at frequencies $f \geq 10$ Hz. At frequencies $2 \leq f \leq 10$ Hz, both of those noise sources of JFET contribute comparable values to the overall ULNA noise. For the high-impedance signal source, the contribution of the JFET shot noise current in the gate circuit and the thermal noise of the JFET biasing resistor shall be also taken into account. The amplifier and the used JFET practically don't exhibit $1/f$ noise at frequencies $f \geq 10$ Hz. The designed ULNA can be used for various low-frequency measurement applications.

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References

[1] B. Neri, B. Pellegrini, and R. Saletti, "Ultra low-noise preamplifier for low-frequency noise masurements in electron devices," *IEEE Trans. Instrum. Measur.*, vol. 40, no. 1, pp. 2–6, Feb. 1991.

[2] F. Shloss, "Accelerometer noise," *Sound Vibr.*, pp. 22–23, Mar. 1993.

[3] F. A. Levinzon, "Noise of piezoelectric accelerometer with integral FET amplifier," *IEEE Sensors J.*, vol. 5, pp. 1235–1242, Dec. 2005.

[4] R. M. Howard, "Low noise amplifier design and low noise amplifiers for characterizing the low frequency noise of infrared detectors," in *Proc. Conf. Optoelectron. Microelectron. Materials Devices*, Perth, WA, Australia, 1998, pp. 179–182.

[5] C. Menolfi and Q. Huang, "A low-noise CMOS instrumentation amplifier for thermoelectric infrared detectors," *IEEE J. Solid-State Circuits*, vol. 32, no. 7, pp. 968–976, Jul. 1997.

[6] M. Lankovec, F. Smole, and M. Topic, "Low-frequency noise measurement of optoelectronic devices," in *Proc. 12th IEEE Mediterranean Electrotech. Conf.*, Ljubljana, Slovenia, 2004, pp. 11–14.

[7] L. K. J. Vandamme, "Noise as a diagnostic tool for quality and reliability of electron devices," *IEEE Trans. Electron Devices*, vol. 41, pp. 2116–2127, Nov. 1994.

[8] B. K. Jones, "Electrical noise as a reliability indicator in electronic devices and components," *Proc. IEEE, Circuits, Devices, Syst.*, pp. 13–22, Feb. 2002.

[9] A. Diligenty, B. Nery, P. E. Bagnoli, A. Barsanti, and M. Rizzo, "Electromigration detection by means of low-frequency noise measurements in thin-film interconnections," *IEEE Electron Device Lett.*, vol. EDL-6, no. 6, pp. 606–608, Jun., 1985.

[10] C. Ciofi, M. De Marines, and B. Neri, "Ultralow-noise PC-based measurement system for the characterization of the metallization of integrated circuits," *IEEE Trans. Instrum. Measur.*, vol. 46, no. 4, pp. 789–793, Aug. 1997.

[11] R. R. Harrison and C. Charles, "A low-power low-noise CMOS amplifier for neural recording applications," *IEEE J. Solid-State Circuits*, vol. 38, no. 5, pp. 958–965, May 2003.

[12] F. Laiwalla, K. G. Klemic, F. J. Sigworth, and E. Culurciello, "An integrated patch-clamp amplifier in silicon-on-sapphire CMOS," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 53, no. 11, pp. 2364–2370, Nov. 2006.

[13] E. Gatty and P. F. Manfredi, "Processing the signals from solid-state detectors in elementary-particle physics," *La Rivista Del Nuovo Cimento*, vol. 9, pp. 75–146, 1986.

[14] F. Evangelisti, "Low-noise FET input amplifier for applications in the audio and subaudio frequency ranges," *IEEE Trans. Audio Electroacoust.*, vol. AE-20, pp. 164–171, 1972.

[15] H. Cheng, M. Qin, D. Gao, and Q. Huang, "A low noise CMOS instrumentation amplifier for integrated thermal gas flow sensor," in *Proc. 7th Int. Conf. Solid-State Integr. Circuit Technol.*, Nanjing, China, 2004, pp. 1831–1834.

[16] G. V. Pallottino and G. Vannaroni, "A low-noise low-input conductance preamplifier for gravitational research," *IEEE Trans. Instrum. Measur.* , vol. IM-34, no. 2, pp. 676–680, Apr. 1985.

[17] F. A. Levinzon, "Noise of the JFET amplifier," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 47, no. 7, pp. 981–985, Jul. 2000.

[18] M. J. Deen and O. Marinov, "Effect of forward and reverse substrate biasing on low-frequency noise in silicon PMOSFETs," *IEEE Trans. Electron Devices*, vol. 49, no. 3, pp. 409–413, Mar. 2002.

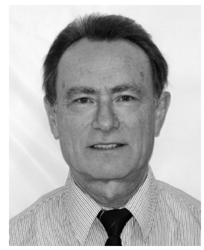
[19] A. Van der Ziel, "Unified presentation of *1/f* noise in electronic devices: Fundamental *1/f* noise sources," *Proc. IEEE*, vol. 76, no. 3, pp. 233–258, Mar. 1988.

[20] S. Kogan, *Electronic Noise and Fluctuations in Solids*. Cambridge, U.K.: Cambridge Univ. Press, 1996.

[21] M. J. Buckingham, *Noise in Electronic Devices and Systems*. New York: Wiley, 1983.

[22] C. D. Motchenbacher and J. A. Connely, *Low Noise Electronic System Design*. New York: Wiley, 1993.

[23] A. Hajimiri and T. H. Lee, "A general theory of phase noise in electrical oscillators," *IEEE J. Solid-State Circuits*, vol. 33, no. 2, pp. 179–194, Feb. 1998.
[24] A. Demir, "Computing timing jitter from phase noise spectra for oscillators and phase-locked loops with white and 1/f noise," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 53, no. 9, pp. 1869–1884, Sep. 2006.
[25] F. A. Levinzon, "Measurement of low-frequency noise of modern low-noise junction field effect transistors," *IEEE Trans. Instrum. Measur.*, vol. 54, no. 6, pp. 2427–2432, Dec. 2005.
[26] *Semiconductor Databook*. Garland, TX: InterFET, 1996, vol. 3.
[27] "Toshiba Field Effect Transistor 2SK369, Specification Sheet," Toshiba Corp., Tokyo, Japan, 2003.
[28] "Toshiba Field Effect Transistor 2SK371, Specification Sheet," Toshiba Corp., Tokyo, Japan, 2003.
[29] Y. Netzer, "The design of low-noise amplifiers," *Proc. IEEE*, vol. 69, no. 6, pp. 728–741, Jun. 1981.
[30] V. Radeka and S. Rescia, "JFET monolithic preamplifier with outstanding noise behavior and radiation hardness characteristics," *IEEE Trans. Nuclear Sci.*, vol. 40, no. 4, pp. 744–749, Aug. 1993.
[31] W. Buttler, B. J. Hosticka, G. Lutz, and P. F. Manfredi, "A JFET-CMOS radiation-tolerant charge-sensitive preamplifier," *IEEE J. Solid-State Circuits*, vol. 25, no. 4, pp. 1022–1024, Aug. 1990.
[32] L. J. Sevin, *Field-Effect Transistors*. New York: McGraw-Hill , 1965.
[33] A. Van der Ziel, *Noise Sources, Characterization, Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1970.
[34] R. S. C. Cobbold, *Theory and Applications of Field-Effect Transistors*. New York: Wiley_Interscience, 1970.
[35] "Aluminum Electrolytic Capacitors, VK Series Miniature Sized, Specification Sheet," Nichicon America Corp., San Diego, CA.
[36] F. A. Levinzon, "Fundamental noise limit of piezoelectric accelerometer," *IEEE Sensors J.*, vol. 4, no. 1, pp. 108–111, Feb. 2004.



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