Very simple FET amplifier with a voltage noise floor less than 1 nV/$\sqrt{\text{Hz}}$

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Abstract. A field-effect transistor (FET) amplifier for small voltage signals is presented. Its design is elementary and the construction can be afforded by anyone. Despite its simplicity, with a voltage noise less than $1\,\text{nV}/\sqrt{\text{Hz}}$, it outperforms commercially available integrated FET amplifiers. The amplifier has a gain flatness better than $1\,\text{dB}$ over $1\,\text{MHz}$ bandwidth; it can be employed as a front-end for signal analyzers or signal recovery systems.

1. Introduction

The experimentalists often need a preamplifier for small voltage signals with an high input impedance and the lowest possible noise.

Amplifiers based on commercial field-effect transistors (FET) integrated circuits (IC) are very simple to construct, and provide a number of friendly properties (internal compensation, wide bandwidth, wide supply voltage range, high power-supply rejection ratio, etc). However, they have equivalent input voltage noise not lower than ≈ 5 nV/$\sqrt{\text{Hz}}$. On the other end, the construction and trimming of amplifiers based on discrete FETs (see e.g. Refs. [1, 2, 3, 4, 5, 6]) could be sometimes tough for the general experimentalist.

In the following, we describe a very simple FET amplifier, which construction simplicity is comparable to those of IC-based amplifiers. It has a number of friendly properties and its voltage noise floor is better than 1 nV/$\sqrt{\text{Hz}}$.

2. The circuit

The circuit is shown in Fig. 1.

The transistor T, directly connected to the input voltage V_{in}, is an FET in an common-source configuration. T works with a gate-source bias voltage $V_{\text{GS}} \approx 0$. ‡

The wiring to V_{in} proposed in Fig. 1 allows a a pseudo-differential configuration. This can help in reducing interferences or, in correlation measurements [7], permits a four-terminal connection to the device under test.

The op amp A works as a transresistance amplifier with gain R, and sets the FET transistor in a cascode configuration [8, 9] (which eliminates the Miller effect [10], thus enhancing the bandwidth). The drain-source voltage V_{DS} is set by A at the voltage V_{B} of the polarization battery B. B is practically unloaded (I_{B} is the small bias current of A), hence it has a long life, and V_{B} has an extremely low noise [11].

A works in a single-supply configuration; its output V_{out} is ac-coupled through capacitor C, and can be further amplified by additional stages if necessary.

The overall low-frequency gain $G = +g_{\text{m}} R$ of the amplifier depends on R and the FET transconductance g_{m}, which can have significant deviations from one sample to another. Therefore, depending on the application, a calibration of G with a reference signal may become necessary [7].

Several other properties of the amplfier, like the compensation, bandwidth flatness, large supply voltage range, high power-supply rejection ratio (PSRR), are given by A.

Typical supply voltage is $V_{\text{CC}} = +24$ V from an unregulated battery; the power load is $\approx 15\,\text{mA}$.

‡ A drawback of such configuration is the limited dynamic range, a few tens of mV at the input, before distortion occurs.

3. Experimental

The circuit is simple to construct and does not require any trimming.

Examples of suitable low-noise FETs are 2SK170 (Toshiba), LSK170 (Linear Systems), LSK389 (dual FET, Linear Systems); Tab. 1 shows an extract of the corresponding datasheets. A prototype has been assembled with a 2SK170, using an OP27 (various suppliers) for A. We set $R = 1\,k\Omega$. The bias current is $2 \div 3$ pA (measured with a Keithley mod. 6430 current meter), which gives a current shot noise less than 1 fA/$\sqrt{\text{Hz}}$.

The transfer function of the amplfier is shown in Fig. 2. It has been measured with a network analyzer (Agilent Tech. mod. 4395A), injecting the signal with a resistive divider ($50\,\Omega$-$0.5\,\Omega$). A $3\,$dB-bandwidth of $\approx 4\,$MHz can be estimated, with a gain flatness better than $1\,$dB up to 1 MHz.

The equivalent input voltage noise with short-circuited input is shown in Fig. 3. It has been measured with a two-channel signal analyzer (Agilent Tech. mod. 35670A) by connecting V_{out} to both channels and performing a cross-correlation measurement in order to reject the analyzer noise. The noise floor is $\approx 0.8\,$nV/$\sqrt{\text{Hz}}$, corresponding to the Johnson noise of a $\approx 38\,\Omega$ resistor at $300\,$K.

4. Conclusions

The amplifier can be of interest in a number of applications, in particular as an input front-end for commercial instrumentation (signal analyzers, lock-in amplifiers).

Two protypes of the amplifier have been employed in a correlation spectrum analyzer, developed for accurate measurement of the Johnson noise of a $1\,k\Omega$ resistor [7]. The experiment is still under development, but the amplifier has shown excellent properties, comparable with more sophisticated setups [6]. Despite the open-loop configuration, after an initial warm-up time the gain mid-term stability is within one part in 10^3 in a laboratory environment.

Acknowledgments

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Table 1. Main specifications of FET models suggested in Sec. 3, from manufacturer datasheets in typical operating conditions.

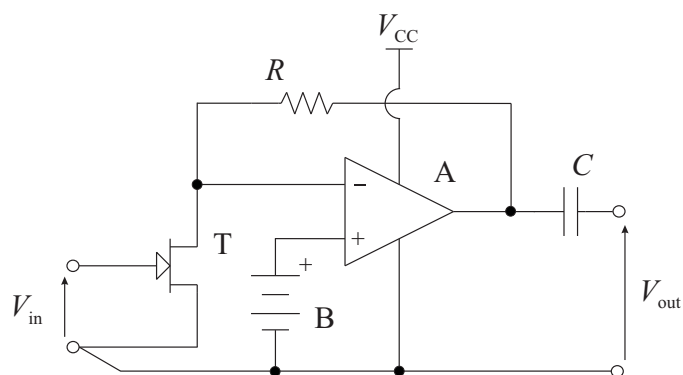| Symbol	description	2SK170BL	LSK170B	LSK389B
g_m	transconductance	$22\,\mathrm{mS}$	$22\,\mathrm{mS}$	$20\,\mathrm{mS}$
e_n	noise voltage ($1\,\mathrm{kHz}$)	$0.95\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$	$0.9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$	$0.9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
C_in	input capacitance	$30\,\mathrm{pF}$	$20\,\mathrm{pF}$	$25\,\mathrm{pF}$
I_DSS	drain current	$6 \div 12\,\mathrm{mA}$	$6 \div 12\,\mathrm{mA}$	$6 \div 12\,\mathrm{mA}$

Figure 1. The schematic of the proposed amplifier. See text for an explanation of the symbols.
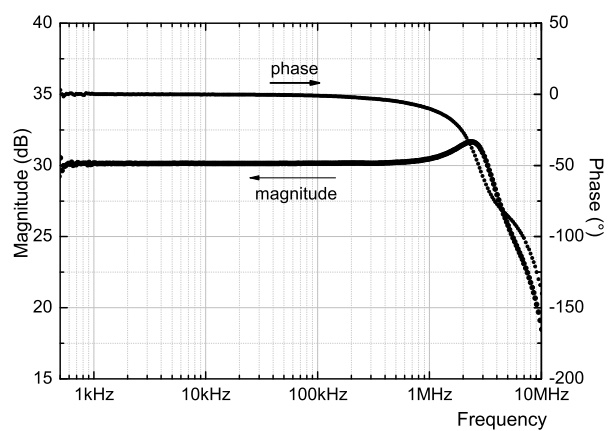

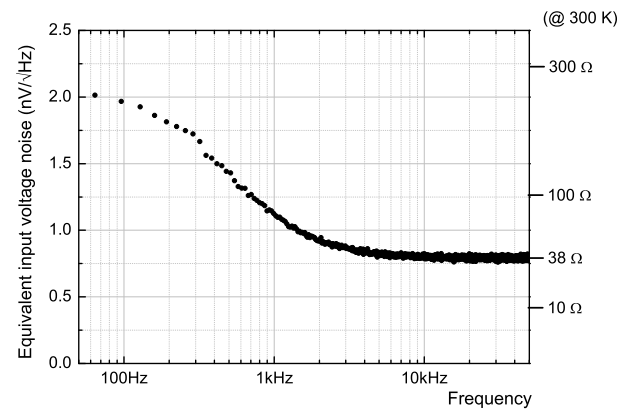**Figure 2.** The transfer function of the amplifier, in magnitude and phase representation.

Figure 3. Equivalent input voltage noise of the amplifier.