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Ultra low noise current sources

C.Ciofi, R.Giannetti, V.Dattilo, B.Neri.
Dipartimento di Ingegneria dell' informazione: Elettronica, Informatica, Telecomunicazioni
v. Diotisalvi 2, I-56126 PISA (Italy)
Phone +39 50 568538 Fax +39 50 568522 E-mail: ciofi@iet.unipi.it

***Abstract* - The current sources which are normally used in research laboratories are not suitable for low noise measurement systems because of the unacceptable level of low frequency noise which they introduce in the measurement chain. The most important source of low frequency noise in such instruments is the solid state device (usually a Zener diode) which is used as voltage reference. By using a novel circuital topology in which a lead battery which does not supply current is used as voltage reference, we have been able to design an ultra low noise current source characterized by a low-frequency noise level some orders of magnitude lower than that of similar commercial instrumentation. The design, realization and testing of such current source is presented in this paper.**

I. INTRODUCTION.

In low frequency noise measurement systems (f<10 Hz), it is often the case that the device under test need to be biased at constant current. Traditional solid state current sources can not be used to this purpose because of the high level of noise which they introduce. Sometimes a battery together with a high value series resistor can be used to simulate a current source. However, such solution becomes impracticable when the current which must be supplied is in the range of hundreds of mA or more. Moreover, the noise produced by the battery dramatically increases if the supplied current overcomes a certain value I_{MAX}, which depends on the type and the capacity of the battery [1]. Normally I_{MAX} is of the order of magnitude of the current at which one hundred hours are sufficient to completely discharge the battery. Finally, it is not possible to maintain the supplied current constant because of the discharge of the battery during the measurements. To overcome the above mentioned problems, purposely designed ultra low noise current sources must be developed.

The topology and the principles of operation of a rather simple ultra low noise solid state current source are described in this paper. By means of an accurate selection of the active and passive components, it has been possible to obtain, in the very low frequency range, a noise level which is orders of magnitude lower than that of instrumentation of the same type available on the market.

II. SYSTEM DESIGN

It is a well known result that batteries behave as low noise voltage sources provided that the current which they supply is very low [1]. In other words, it is possible to employ a battery as a very low noise voltage reference. In fact, in low frequency noise measurements, a high accuracy in the value of the supplied current, as that which could be obtained by means of a Zener diode, is normally not important. It is much more important to keep the background noise of the system to a minimum. In the circuit reported in Fig.1, already proposed in [2], a battery which does not supply current is employed for biasing a low-noise FET (8 2SK146 by Toshiba in parallel) used as current source.

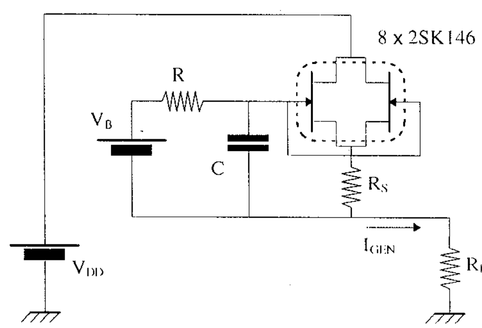

Fig.1. Schematic of the ultra low noise current source.

In Fig. 1 R_L represents the load. By neglecting the gate-to-source voltage (a few hundreds of millivolts for this transistor), the current supplied to the load is given by :

$$I_{\mathrm{GEN}} = \frac{V_{\mathrm{B}}}{R_{\mathrm{S}}} \qquad (1)$$

The value of I_{GEN} can be adjusted by selecting an appropriate value for R_{S}. The most important source of low frequency noise in the previous circuit is the input equivalent voltage noise source $e_{n\mathrm{FET}}$ of the FET. Therefore, the power spectral density $Si_{n\mathrm{GEN}}$ of the current fluctuations in the load is given by :

$$Si_{n\mathrm{GEN}} = Se_{n\mathrm{FET}} \left[\frac{g_m}{1 + g_m R_{\mathrm{S}}} \right]^2 \qquad (2)$$

where $Se_{n\mathrm{FET}}$ is the power spectral density of e_n and g_m is the transconductance of the FET. In many cases, (2) reduces to :

$$Si_{n\mathrm{GEN}} \cong \frac{Se_{n\mathrm{FET}}}{R_{\mathrm{S}}^2} = Se_{n\mathrm{FET}} \left(\frac{I_{\mathrm{GEN}}}{V_{\mathrm{B}}} \right)^2 \qquad (3)$$

since, normally, $g_m R_{\mathrm{S}} >> 1$.

This circuit, however, has some drawbacks. First of all, it is not easy to find on the market the active components which we have used, since they are now produced by the manufacturer only upon request and, therefore, only for very large quantities. Moreover, the simple topology shown in Fig.1 suffers from a serious limitation : if the power dissipated by the FET increases (as it happens when a high value of I_{GEN} has to be delivered to a low resistance load) the effects of the temperature fluctuations of the active devices cause a remarkable degradation of the noise characteristics [1]. However, since the Joule heating depends on the product $I_{\mathrm{GEN}} \cdot V_{\mathrm{DS}}$, V_{DS} being the source to drain voltage of the FET, this undesired effect could be reduced by maintaining the voltage V_{DS} as low as possible, independently of the supplied current.

This result has been obtained in the circuit reported in Fig. 2 in which a different type of active device (two IF3601 by Interfet in parallel), easily available on the market, is employed.

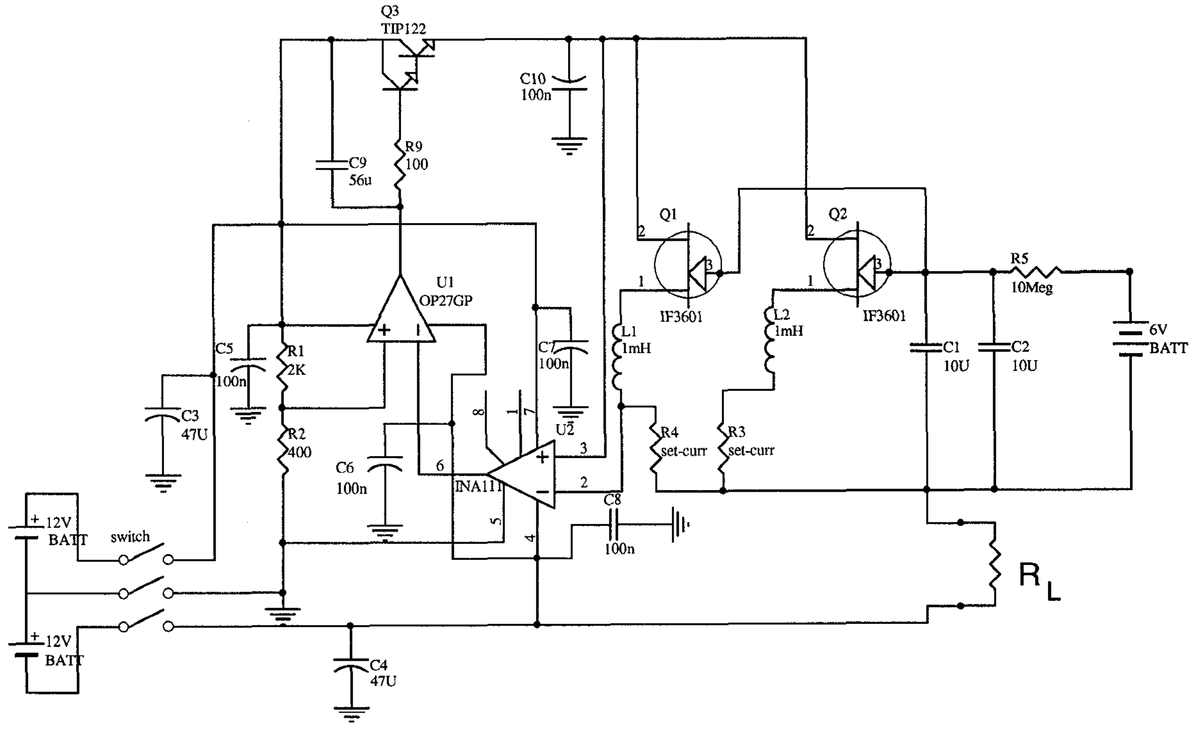

Fig. 2. Schematic of the new ultra low noise current source.

The peculiarity of this circuit lays in the fact that the voltage V_{DS} is kept constant by means of the feedback loop U2-U1-Q3. The operation of such feedback loop is as follows : the differential amplifier U2 (INA111, gain=1) reads the differential voltage V_{DS} and provides the inverting input of the high gain operational amplifier U1 (OP-27) with a voltage, referred to ground, equal to V_{DS}. The voltage which is present at the non-inverting input of U1, obtained by means of the voltage divider R_1/R_2, is equal to the desired value of V_{DS}. The operational amplifier U1 acts as an error amplifier and drives the transistor Q3 (a Darlington type TIP122) which sets the value of the voltage at the drain of the FETs.

At equilibrium; the voltage difference between the inverting and non inverting input of U1 is approximately zero, which implies that V_{DS} is equal to the desired value. Such value is about 2 V, and it is the result of a compromise between the need to reduce the power dissipated by the FETs and the need to maintain them in the saturation region.

In order to reduce the effects of thermal transients or of accidental mechanical shocks, which could cause slow fluctuations of the output current, an *RC* low pass filter (R_5, C_1+C_2) with a corner frequency of 0.8 mHz, has been interposed between the battery and the gates of the FETs. The values of R_5 and of C_1+C_2 (10 MΩ and 20 μF, respectively) have been chosen in such a way as to make the contribution of the thermal noise of the resistor R_5, in the frequency range above 10 mHz, negligible.

III. MEASUREMENTS

The measurements have been performed by using metallic film, excess noise free, resistors for R_L. Different values of the output current have been set by changing the resistors R_3, R_4 (R_3=R_4) which have the same function as the resistor R_S in the circuit in Fig. 1. An ultra low noise preamplifier, described in [3] was employed in order to measure the power spectrum Se_{nGEN} of the voltage fluctuations across R_L for any supplied current. The measurement of Se_{nGEN} provides us with a means for the evaluation of the spectrum Si_{nGEN} of the current fluctuations through the load. In fact, it results :

$$Si_{n\mathrm{GEN}} = \frac{Se_{n\mathrm{GEN}}}{R_\mathrm{L}^2} \tag{4}$$

However, for a correct evaluation of Se_{nGEN} we must take into account the noise introduced by the preamplifier and the thermal noise of R_L.

The power spectrum S_{V_i} of the voltage fluctuations at the input of the preamplifier is given by the following relationship :

$$Sv_\mathrm{i} = Se_{n\mathrm{GEN}} + Se_{n\mathrm{P}} + R_\mathrm{L}^2 Si_{n\mathrm{P}} + Se_{n\mathrm{TH}} \tag{5}$$

where Se_{nP} and Si_{nP} are the power spectra of the input equivalent voltage and current noise sources of the preamplifier, while the term Se_{nTH} accounts for the thermal noise of R_L.

The total contribution S_{BN} resulting from Se_{nP}, Si_{nP} and Se_{nTH} was evaluated by disconnecting the current source and by leaving R_L alone at the input of the preamplifier. The spectrum Se_{nGEN} was then evaluated by subtracting S_{BN} from the measured spectrum S_{V_i}.

The spectra reported in Fig. 3 have been obtained following the procedure outlined before with two different values of the supplied current I_{GEN} (23 and 46 mA) and with the same value for R_L (200 Ω). The spectra have a typical $1/f^{\gamma}$ behavior with a value of γ close to 1.5 in the frequency range from 5 mHz to 1 Hz. A comparison of the spectra in Fig. 3 with the spectrum of the equivalent input voltage noise source e_{nFET} of the FET, which have been independently measured, allow us to conclude that they are consistent with (3), that is Si_{nGEN} is essentially due to the noise introduced by the FETs.

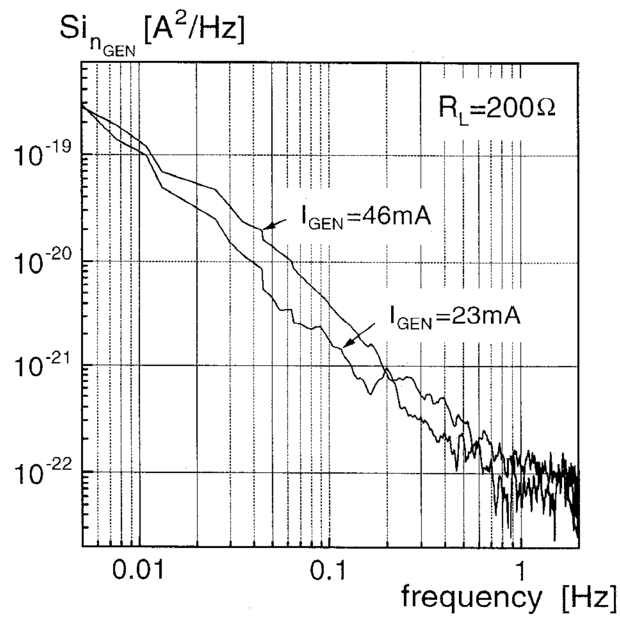

Fig.3. Power spectra of the current fluctuations at the output of the ultra low noise current source.

The difference between the two spectra in Fig. 3 are due to the different values of the resistances (R_3,R_4) needed for obtaining the two different values of I_{GEN}.
In order to ascertain the dependence of Si_{nGEN} on the DC voltage across R_L, a set of measurement were performed at the same value of the supplied current (23 mA) but with different values of the load resistance R_L. The value of $(Si_{nGEN})^{1/2}$ at the frequency of 50 mHz is reported in Fig. 4 versus R_L. As it can be seen, for a given value of the supplied current, Si_{nGEN} is essentially independent of the load resistance and, hence, of the output voltage V_{GEN}.

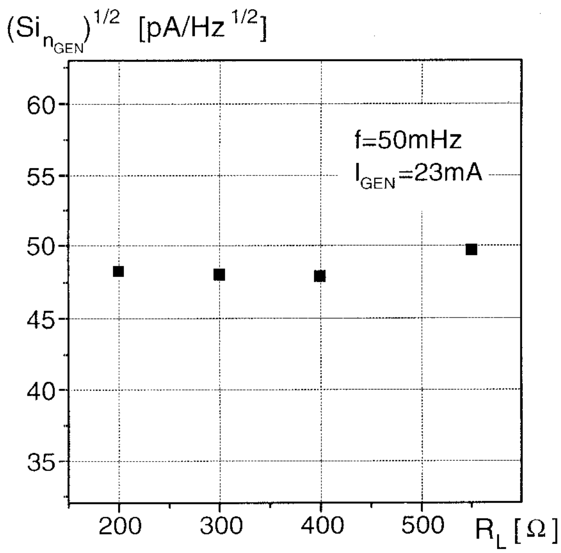

Fig.4. Output current noise spectral density (f=50mHz) as a function of the load resistance. The supplied current is 23 mA.

IV. CONCLUSIONS

The design, realization and testing of an ultra low noise current source has been described. The most interesting characteristic of the instrument, at present used for noise measurements in metal stripes for integrated circuits, is the extremely low level of the background noise. The careful design and the accurate selection of active and passive components, have allowed us to obtain noise levels similar to those which were previously possible only by means of low noise batteries. For a supplied current of about 50 mA, some typical values of the output equivalent current noise i_{nGEN} of the new current source are: 110, 49, 12 pA/(Hz)$^{1/2}$ at 0.05, 0.2 and 1 Hz, respectively. The excellent noise performances of the instrument makes it particularly suitable for applications in ultra low noise measurement systems, where a quasi-ideal current source is required.

ACKNOWLEDGMENT

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