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A VERY LOW NOISE, HIGH STABILITY, VOLTAGE REFERENCE FOR HIGH SENSITIVITY NOISE MEASUREMENTS

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In this paper we demonstrate that by exploiting the non linear characteristic of low noise *PN* junction diodes, a very low noise, high stability voltage reference can be obtained starting from a conventional solid state series voltage reference. In order to obtain such a result, a series connection of N identical diodes is supplied in the forward region of the I-V characteristic by means of a proper resistance. While the DC voltage drop across the diodes can be a large fraction of the voltage supplied by the reference, the noise introduced by the reference itself is reduced by a much larger factor because of the low value of the small signal equivalent resistance of the diodes. In its simplest implementation, such a voltage source would suffer from a relatively high temperature dependence of the supplied voltages because of the intrinsic properties of *PN* junctions. However, by resorting to a proper temperature control circuit, high stability can be obtained. As an example, by employing an AD586 voltage reference and with $N = 4$, a 2.560 V reference has been obtained with a stability over temperature better that 50 μV/°C and a voltage noise as low as 2×10^{-15}, 6×10^{-17} and 1.5×10^{-17} V^2/Hz at 100 mHz, 1 Hz and for frequencies larger than 10 Hz, respectively.

Keywords: Low noise instrumentation; voltage reference; temperature stability.

1. Introduction

The sensitivity of any low noise measurement chain is ultimately limited by the equivalent input noise sources of the input preamplifier coupled to the device under test (DUT). However, other sources of noise or fluctuations may be present which considerably contribute to the background noise of the entire system. Besides electromagnetic interferences and the effect of mechanical vibrations, which can be reduced by means of proper shielding and the use of anti-vibrating benches, the noise produced by the instrumentation employed for biasing the DUT is a major concern. As a general rule, solid state voltage or current references cannot be employed as they introduce an unacceptable large additional noise. When the lowest frequency of interest is above a few Hertz and the current to be supplied is not large, filtering may prove effective in reducing the noise introduced by solid state reference sources. However, in the large field of the application of low frequency noise measurements to the characterization of the quality and reliability of electron devices, where the frequencies of interest may be as low as a few tens of mHz [1,2], filtering can seldom be effective. Therefore, in order to avoid such supplemental source of noise, high capacity batteries are normally used for biasing the DUT. Using batteries, however, poses several important limitations: only a few voltages are normally available, and their exact values strongly depend on the charge status of the batteries and on their age; a programmable biasing system can not be realized using batteries, and even if we resort to a programmable switching network which varies the number of the batteries connected in series, the minimum voltage step which can be obtained is that of the elementary cell (about 2 V in the case of lead-acid batteries). Sometimes, a resistive divider network can be used in order to obtain voltages different from integer multiples of the elementary cell voltage, but in this case low resistance values must be used in order to reduce the thermal noise contribution of the voltage divider itself. This results in rather high currents supplied by the battery with a degradation of the noise performances and a significant drift of the supplied voltage because of the fast discharge. Clearly, one may reduce such a problem by means of very high capacity batteries, but this would not be practical in most cases. In the past we have addressed the problem of the realization of a programmable, very low noise voltage reference and we did actually come out with two possible solutions to this problem [3,4]. In the first approach we had a very low noise reference that was however characterized by low stability; in the second case we had a rather stable source (a solid state DA converter) but with a high level of noise whose reduction made the system too complex to be appealing for other researchers involved in the field. Therefore it was clear that the starting point for a sensible realization of a programmable low noise, high accuracy voltage source was the realization of a high stability, low noise voltage reference characterized by a low degree of complexity. This is what we believe we have achieved in this work and we trust that our approach may be the starting point toward the realization of highly compact and low cost programmable, very low noise, voltage sources.

2. Low Noise, Temperature Uncompensated, Voltage Reference

In its simplest form a low noise voltage reference can be realized as in Fig. 1. A series of N diodes is supplied by a solid state voltage reference through a resistance R_S. In our implementation, each diode was obtained starting from an SSM2220 low noise matched pair of PNP transistor. One transistor for each pair was connected as a diode by shorting the base and the collector terminals. For the present discussion, we can ignore the presence of the second transistor. In fact, as it will be discussed in the following sections, it was used in order to provide for temperature compensation. The SSM2220 were selected as the devices with the lowest level of flicker noise among those we had available.

As a voltage series regulator we selected the AD586 5 V reference by Analog Devices. While it is referred to as a "low noise" voltage reference, the power spectrum of the voltage fluctuations at its output are in the order of 2×10^{-13}, 2×10^{-14} and 8×10^{-15} V^2/Hz at the frequencies of 0.1, 1 and for frequencies above 10 Hz, respectively. Such values are too high for many low frequency noise measurement applications. The number N of diodes sets the output voltage, while the resistance R_S has little effect on it, as it can be observed in Fig. 2, where we report the load curve for a few values of R_S and a few values of N.

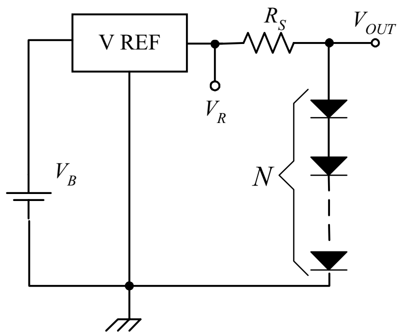

Fig. 1. A simple implementation of a low noise voltage reference. The number N of diodes connected in series together with the values of R_S and of the reference voltage V_R set the output voltage.

The value of R_S, however, sets the current flowing through the diodes, thus setting the value of their small signal equivalent resistance. In the case of the SSM2220, in the current range of a few mA, the voltage drop across each diode is about 0.64 V. Therefore, with $N = 4$, we can obtain an output voltage of about 2.56 V. The basic idea underlying the approach we propose is that, while the voltage drop across the diodes can be a significant fraction of the voltage supplied by the solid state reference, their equivalent resistance can be made to be a small fraction of the resistance R_S, thus causing a large attenuation of the voltage noise that is generated by the solid state reference.

It must be noted that such an attenuation is independent of the frequency and that the output resistance of the source is of the order of the equivalent resistance of the series of the N diodes. In a sense, therefore, we have obtained an ideal filter that attenuates by the same amount all the frequencies but the DC.

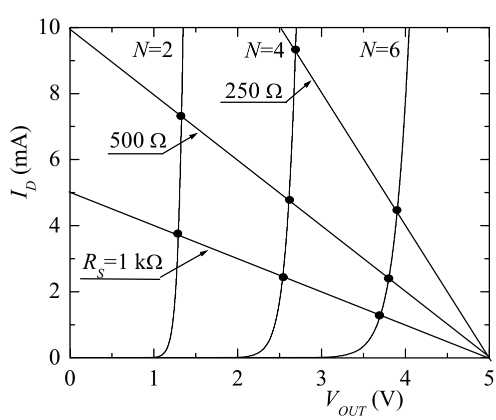

Fig. 2. Operating points for the circuit in Fig. 1 for a few values of N (N = 2,4,6) and R_S. The curves representing the I-V characteristics of the series connected diodes (SSM2220) were obtained by direct measurement at room temperature. For drawing the load curve we assumed a voltage reference V_R = 5 V.

Moreover, the settling time of the system is negligible. As it could be easily demonstrated, obtaining the same attenuation at 100 mHz, that from now on we will regard as the lower frequency we are interested in, would require a low pass filter with a very low corner frequency that would result in an unacceptably long settling time and, because of the need of high series resistances, in a very large output impedance[4]. Once the reference voltage and the number of diodes are chosen, we need to select the value of R_S in such a way as to reduce the overall output noise. However, also the output impedance of the voltage source must be taken into account as we would like to have it as low as possible. As a first step, therefore, we will analyze the noise performance of the circuit as a function of the value of the resistance R_S. There are three contribution to the output noise: a) the noise generated by the solid state voltage reference e_V; the noise introduced by the resistance e_R; c) the noise e_D introduced by the series of N diodes. For the sake of simplicity, we will limit our discussion to the white region of the noise spectra, where the diodes contribute to the noise with the shot noise component only. As far as the DC behavior of the series of N diodes is concerned, it can be easily demonstrated that it is equivalent to a single diode whose current voltage characteristic is given by the following expression:

$$I = I_0 \left(e^{\frac{V_{OUT}}{NV_T}} - 1 \right) \tag{1}$$

where I_0 is the saturation current corresponding to one single diode, V_{OUT} is the total voltage across the series of N diodes and V_T is the voltage equivalent of the temperature ($V_T = 0.0259$ V at room temperature). For a given DC forward current I, provided that $I >> I_0$ as it is the case in our situation, the small signal equivalent resistance of the diodes is equal to $N\, r_D$, where

$$r_D = \frac{V_T}{I} \tag{2}$$

is the small signal equivalent resistance of one single diode. As for the noise contribution due to the shot noise, we can assume the current noise equivalent sources in parallel to each diode (with a power spectral density $2qI$, where q is the electron charge) to be uncorrelated and therefore, it can be demonstrated that their overall effect can be accounted for by means of an equivalent voltage noise source in series to the diodes with a power spectral density S_{eD} given by :

$$S_{e_D} = N2qIr_D^2 = 2KTNr_D \tag{3}$$

where we have used the identity $V_T = KT/q$, K being the Boltzmann constant and T the absolute temperature. The noise produced by the voltage reference is largely independent of the supplied current and we will assume, in the white region of the spectra, a value for S_{EV} of 8×10^{-17} V^2/H_Z. Such a value corresponds to what was actually measured at the output of the AD586 voltage reference used in the prototype we have realized and tested. Finally, the noise voltage in series to R_S, representing the noise contribution of the resistance, does depend on the value of the resistance itself as we have:

$$S_{e_R} = 4KTR_S \tag{4}$$

According to the small signal equivalent circuit in Fig. 3, the power spectral density at the output of the voltage reference can be calculated as follows:

$$S_{V_{OUT}} = \left(S_{eV} + 4KTR_S\right)\left(\frac{Nr_D}{R_S + Nr_D}\right)^2 + 2KTNr_D\left(\frac{R_S}{R_S + Nr_D}\right)^2 \qquad (5)$$

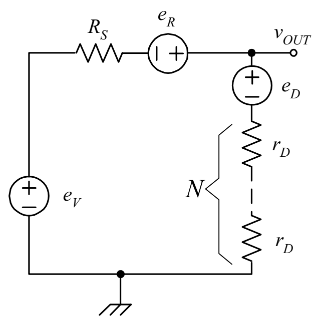

Fig. 3. Small signal equivalent circuit for the calculation of the output voltage noise. The equivalent noise source e_D accounts for the noise introduced by the N diodes as discussed in the text.

As we have noted before, the voltage drop across the diodes remains roughly constant even for large changes in the value of the series resistance R_S. Therefore also the voltage drop across the resistance R_S remains almost constant and independent of the value R_S. Moreover, in the case of our example, with $N = 4$ we obtain a voltage drop across the diodes which is about half of the reference voltage. Since near room temperature V_T is of the order of 26 mV, we have that in our operating condition, whichever the value of R_S within a rather large range,:

$$R_S I >> NV_T \;\Rightarrow\; R_S >> N\frac{V_T}{I} = Nr_D \qquad (6)$$

Therefore, Eq. (5) can be approximated as follows:

$$S_{V_{OUT}} \approx \left(S_{eV} + 4KTR_S\right)\left(\frac{Nr_D}{R_S}\right)^2 + 2KTNr_D \approx S_{eV}\left(\frac{NV_T}{R_S I}\right)^2 + 4KTR_S\left(\frac{NV_T}{2R_S I}\right) \qquad (7)$$

If we select R_S in the order of 1 kΩ, in the case of the AD586 5 V voltage reference and N=4 we would have a current I supplied by the solid state reference of about 2.44 mA and:

$$NV_T \approx 104\, mV;\; R_S I \approx 5 - 2.56 = 2.44\, V;\; \frac{2R_S I}{4V_T} \approx 47;\; \left(\frac{R_S I}{NV_T}\right)^2 \approx 550 \qquad (8)$$

Therefore we can obtain a reduction of about 27 dB in the noise introduced by the solid state voltage reference and a reduction of about 17 dB in the noise introduced by the series resistance R_S. Changing the resistance R_S does not affect the output noise significantly, as the noise introduced by the resistance is small compared to the noise introduced by the solid state voltage reference. However, smaller values for R_S result in larger currents and, therefore, lower output impedance. As an example of the performances that can be obtained, we report the results of noise measurements performed in the case $R = 560\ \Omega$ ($I \approx 4.4$ mA) in Fig. 4. The output voltage is about 2.57 V with an output impedance of 23 Ω. As it can be noted, the output noise is exactly what is expected from Eq. 7.

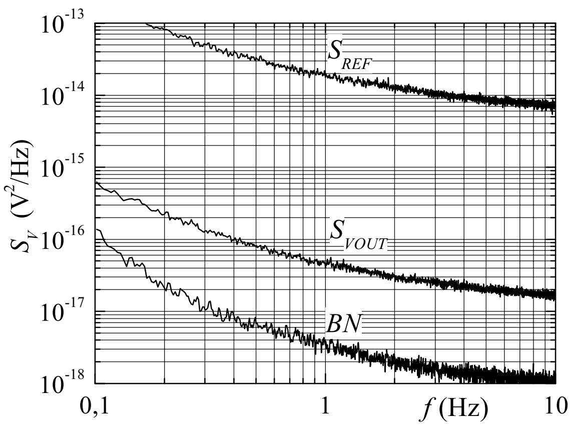

Fig. 4. Power spectral density of voltage fluctuations measured on the circuit in Fig. 1. S_{VOUT} is the spectrum of the voltage fluctuations at the output of the system; S_{REF} is the spectrum of the voltage noise at the output of the solid state voltage reference AD586, *BN* is the equivalent input noise of the ultra low noise amplifier employed for the measurements.

3. Low noise, Temperature Compensated, Voltage Reference

In order to stabilize the output voltage against ambient temperature changes, we need to obtain a very tight control over the temperature of operation of the series of N diodes used to obtain the low noise voltage reference discussed in the previous section. The approach we have followed is based on the fact that a highly stable voltage reference is available that supplies the low noise voltage reference and that two independent transistors are integrated within each SSM2220 package. In fact, we use one of the transistors for each package for obtaining the diode needed in the circuit in Fig. 1, while we connect the other in such a way as it can be used as a micro-heather for the former, as in Fig. 5. The highly stable voltage reference is used to obtain a reference voltage V_{SET} equal to what is expected to be the output voltage across the N diodes at the design temperature.

A PI (proportional-integral) control feedback is realized by using the differential amplifier AD620 together with the circuit including an integrator (AD743) and a summing circuit (OP27). The control was designed in such a was as to introduce an as low as possible additional noise through the thermal coupling inside each SSM2220. This resulted in a rather slow time constant that required the N SSM2220 to be mounted in contact with a 25 g brass thermal mass and to be wrapped in cotton in order to obtain a sufficiently long low pass thermal constant that allowed to shield the system from fast environmental temperature changes. The heating system is capable of granting about 3 ^{o}C maximum temperature change in the temperature of the diodes used as voltage reference. The results that have been obtained in the case of N=4 and by setting a target voltage of 2.560 volts (corresponding to an operating temperature of about 27 ^{o}C are summarized in Fig. 6

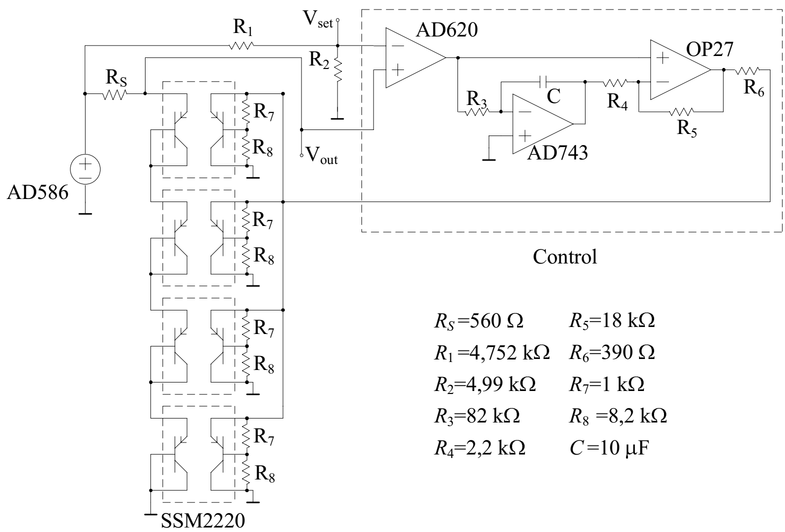

Fig. 5. Complete schematic of the low noise voltage reference including the temperature compensation system. The circuit within the dashed box acts as an error amplifier with a proportional-integral action. By changing the current supplied to the transistors used as heaters, the voltage V_{OUT} is made to approach the target voltage V_{SET}.

and Fig. 7. In Fig. 6 we report the value of the voltage V_{OUT} as measured by a high accuracy 8½ digits multimeter (Agilent 3458A) as a function of the temperature of the thermal chamber within which the entire system was enclosed.

During the experiment, the temperature of the thermal chamber was made to decrease from 30 to 20 °C in about 20 hours. As it can be noted, when within the temperature tracking range (external temperature from about 22.2 to about 24.8 °C), the output voltage changes by about 50 μV (less than 20 ppm with respect to the set voltage V_{SET}). The result of noise measurements performed while within the thermal capture range of the controller in the same experimental conditions as before are reported in Fig. 7. As it can be noted, above about 3 Hz, there is no difference in the power spectrum obtained with (S_{VCONT}) and without the temperature control system (S_{VOUT} as in Fig. 4).

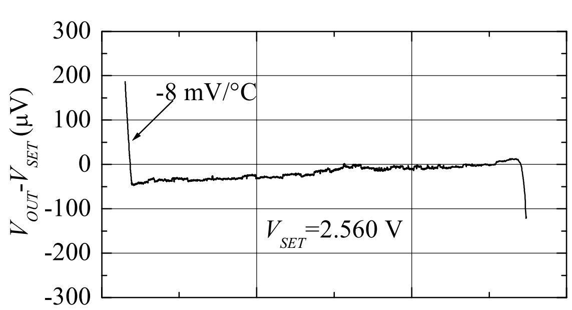

Fig. 6. Voltage error (V_{OUT}-V_{SET}) at the output of the circuit in Fig. 5 versus external temperature. The temperature control system is active in the range from 22.2 to 24.8 °C. Outside this range the temperature control circuit is saturated and therefore the temperature coefficient of the voltage source is -2*N* mV/°C.

At lower frequencies, however, we obtain a higher level of noise that depends on the action of the temperature control system. It must be noted that it is possible, in principle, to change the control parameters in order to trade noise at lower frequencies for temperature stability.

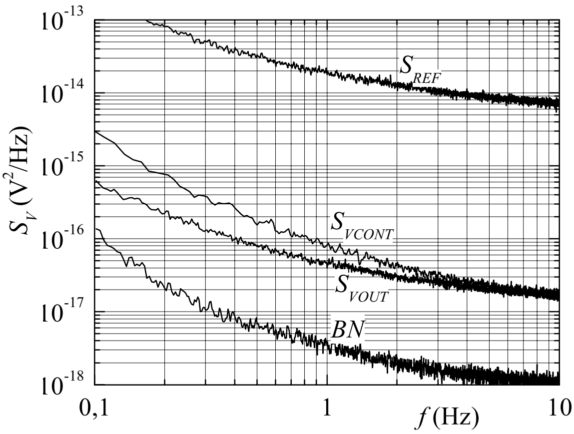

Fig. 7. Power spectral density of voltage fluctuations measured at the output of the circuit in Fig. 5 (S_{VCONT}). The power spectrum S_{VOUT} of the voltage fluctuations at the output of the circuit in Fig. 1 is reported as a reference.

4. Conclusions

In this paper we have discussed a very simple and effective approach for the realization of high stability, low noise voltage references. While we trust that the results we have obtained so fare may be attractive for many researchers involved in the field, especially because of the low complexity of the design we propose, we believe that there is ample margin for further improvements. In fact, in our deign the solid state reference noise reduction factor cannot be changed once the output voltage is chosen. However, as such a reduction factor is large (a few hundreds in the case of the tested prototype), preliminary moderate filtering at the output of the solid state reference may become possible, as an attenuation of the noise by 10 or 20 dB at 100 mHz can be obtained with reasonable time constant. This would allow, when combined with the noise reduction system we propose, to reach much lower level of output noise. Further work is however needed in order to exploit other possible improvement and to assess the ultimate noise an stability performances that can by obtained.

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