A New Circuit Topology for the Realization of Very Low Noise, High Stability Voltage Sources

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***Abstract*—A new topology for the realization of high-stability very low noise voltage references is presented. The topology relies on a self-biasing circuit configuration based on a low-noise operational amplifier (OA). The series connection of a number of forward-biased low-noise diodes is used as an internal reference for generating any desired output voltage. The circuit may include a temperature stabilization system for obtaining very high stability coupled to very low noise. As an example, a 5-V reference with an output power spectral density of as low as 22 nV/$\sqrt{}$Hz at 100 mHz, 7 nV/$\sqrt{}$Hz at 1 Hz, and less than 6 nV/$\sqrt{}$Hz for frequencies larger than 10 Hz can be obtained with a temperature stability better than 15 μV/°C (less than 3 ppm/°C).**

***Index Terms*—Circuit noise, noise measurement, semiconductor device noise, temperature control, voltage control.**

I. Introduction

VERY low noise voltage and current sources are often required as part of low-frequency noise measurement systems. In particular, those voltage or current sources employed for biasing the devices under test must be characterized by a very low level of noise to not contribute to the background noise of the system [1]. Conventional voltage or current sources, which are usually based on a Zener solid-state voltage reference, are characterized by a very high level of noise, particularly at very low frequencies, and they cannot be used in high-sensitivity noise measurement systems. Therefore, batteries are almost always used as low-noise voltage sources in the field of low-frequency noise measurements [2]. When current sources are required, they can be obtained by resorting to a series connection of a few batteries with a conveniently large series resistance. Indeed, large-capacity batteries can behave as very low noise sources provided that the supplied current is much lower than those for which they are rated. Using batteries, however, has some important drawbacks. First of all, batteries need to often be recharged, they do not supply a constant voltage, and the supplied voltage can only be an integer multiple of the elementary cell voltage. One can indeed resort to resistive voltage dividers to obtain any desired voltage, but the large current flowing through the voltage divider does inevitably cause a fast discharge of the batteries. Moreover, it is usually observed that after several discharge/charge cycles, the discharge rate, and therefore the voltage or current drift during experiments, and the noise introduced in the circuit do increase [3]. It is for these reasons that a few attempts have been made in the past for the design and realization of very low noise voltage or current sources that could allow overcoming some of the limitations previously mentioned. In a first approach, a small-capacity lead acid battery supplying a negligible current was used as a voltage reference, around which a programmable low-noise voltage source was built capable of supplying several hundred milliamperes [4]. The very same principle was used for the realization of an ultralow-noise current source [5] that has found application in nuclear physics experiments [6], [7]. The reference battery voltage drifts due to temperature changes and self-discharge were the most important limitation of these approaches. In a second approach, the possibility of filtering out the noise produced by a solid-state voltage reference for realizing a very low noise voltage source was investigated. The difficulty in this approach was the need of obtaining an attenuation of more than 40 dB of the noise produced by a solid-state reference at frequencies as low as 100 mHz, which required the design of a rather complex filtering section, including a microcontroller-based unit for managing the operation of the entire system and for compensating temperature-induced drift [8].

While such approaches proved effective as far as the goal of obtaining a very low noise was concerned, they indubitably suffered from the limitation of being based on rather complex designs. More recently, a third approach was followed that appeared to be quite promising both in terms of effectiveness in obtaining a very low noise voltage reference and in terms of reduced complexity [9]. In this approach, we take advantage of the nonlinear characteristics of low-noise silicon diodes in the very simple circuit configuration reported in Fig. 1. The low-noise silicon diodes are obtained by resorting to the very low noise silicon transistors SSM2220 by Analog Devices. Because of their nonlinear characteristics, in the circuit in Fig. 1, a dc voltage drop across the diodes can be obtained, which may be a significant fraction of the reference voltage V_{REF}. At the same time, the diodes are characterized by a very low differential resistance, which can be much smaller than R_B, thus causing a strong attenuation, at all frequencies, of the noise introduced by the solid-state voltage reference. In addition to the high-temperature dependence of the reference voltage that can be, however, considerably reduced by means of a proper temperature control system, the main limitations of this approach are the fact that the output voltage can only be an integer multiple of the voltage drop across each diode and that the minimum noise level is set by the noise produced by the solid-state reference generating V_{REF} that cannot be reduced beyond a given factor [9]. To solve these problems, a self-biasing circuit can be used

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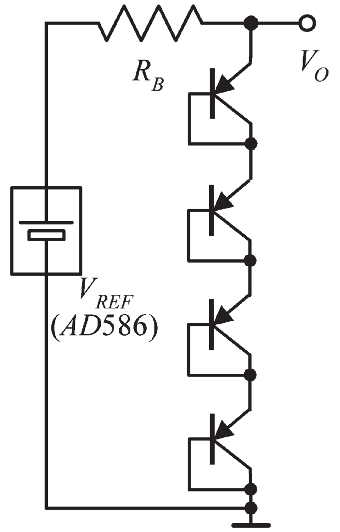

Fig. 1. Very simple low-noise voltage reference as proposed in [9].

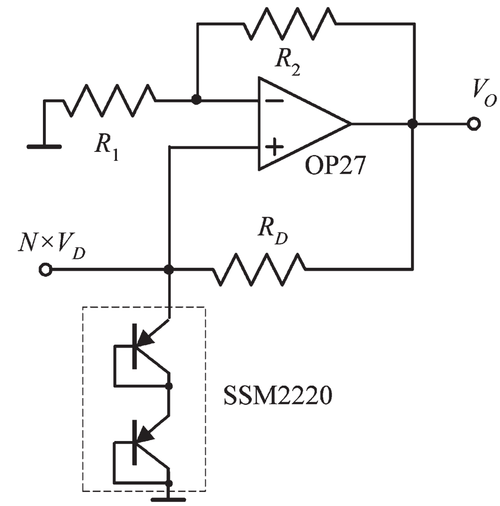

Fig. 2. Schematic of the new low-noise voltage reference. Reprinted with permission from C. Ciofi, G. Scandurra, and G. Cannatà, "A new circuit topology for the realization of low noise voltage references," *Proceedings of the 20th International Conference on Noise and Fluctuations* (*ICNF* 2009), Pisa, Italy, 14–19 June 2009, 599–602 Copyright 2009 American Institute of Physics.

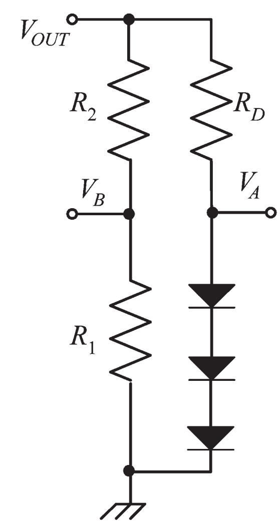

Fig. 3. Simplified circuit for calculating the equilibrium point of the circuit in Fig. 2 ($N = 3$ is assumed).

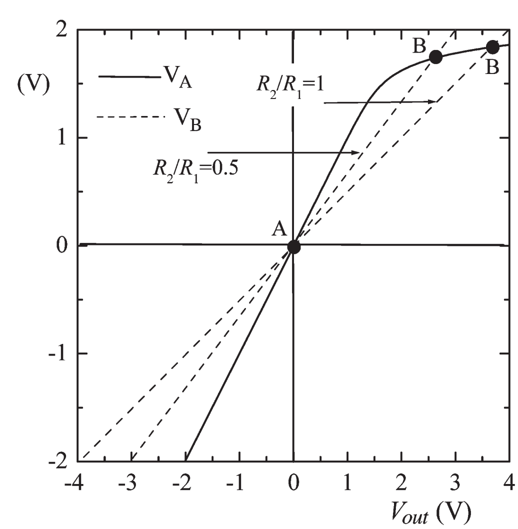

Fig. 4. Voltages V_A and V_B in the circuit of Fig. 3 as a function of the voltage Vo for different values of the ratio R_2/R_1. Two equilibrium points exist for each ratio R_2/R_1, labeled A and B in the figure.

in such a way as to have the series of diodes biased in the forward region of operation without the need for an external reference voltage. This approach is very much like that used in some solid-state reference systems, such as the REF 102 by Texas Instruments [10], with the Zener diode replaced by the series of N low-noise diodes in the forward region of operation. A prototype of such a system was indeed realized and tested, obtaining quite interesting preliminary results that have been reported in [11]. We decided, therefore, that it was worth to explore the full potentiality of this approach. Such an investigation is indeed the subject of this paper. By means of an accurate analysis on the influence of all circuit parameters on the output noise, it has been possible to establish the design guidelines to be followed for obtaining optimum noise performances. The problem of the stabilization of the output voltage against temperature changes is also discussed in detail.

II. New Low-Noise Voltage Reference

A schematic of the new low noise voltage reference is reported in Fig. 2. As it was anticipated in Section I, the circuit configuration is very much like that employed in the solid-state reference REF 102 by Texas Instruments [10]. The novelty of the approach consists of employing a series of low-noise forward-biased diodes, instead of a Zener, as a reference source. The operational amplifier (OA) OP27 has been selected because of its very low equivalent input voltage noise (EIVN). Indeed, it is the EIVN of the OA that, as it will be shown in the following, sets the minimum level of noise at the output V_O. The circuit can be regarded as a nonlinear self-balancing bridge. The possible values of the output voltage V_O, assuming virtual short circuit at the input of the OA, are those for which $V_A = V_B$ in Fig. 3 (we assumed $N = 3$ diodes). The plots of V_A and V_B versus V_O are reported in Fig. 4. As it is apparent from the figure, for any ratio R_2/R_1, two equilibrium points are obtained. It can easily be demonstrated that the equilibrium point A is unstable, whereas the equilibrium point Bs are stable. Indeed, we can estimate the small signal gain A from the OA input to output and the feedback gain β from the output of the OA back to its input. In the hypothesis of dominant pole compensation and of infinite input impedance and output admittance for the OA, we have

$$A(s) = \frac{A_{V0}}{1+s\tau_{OP}} \quad \beta = \left(\frac{1}{1+R_D/Nr_D} - \frac{1}{1+R_2/R_1}\right) \tag{1}$$

where A_{V0} is the dc open-loop gain of the operational amplifier, τ_{OP} is the time constant corresponding to the dominant pole compensation, and r_D is the small-signal equivalent resistance of each diode at any given bias point. In this approximation, the system is characterized by a single pole that can be calculated by solving the equation $T(s)+1=0$, where $T(s)=-\beta A$ is the return ratio. For the pole s_p, we therefore have

$$s_p = \frac{1}{\tau_{OP}}\left[A_{V0}\left(\frac{1}{1+R_D/Nr_{dD}} - \frac{1}{1+R_2/R_1}\right) - 1\right]. \tag{2}$$

For the system to be stable, the following condition must be verified:

$$\frac{1}{1+R_D/Nr_D} < \frac{1}{1+R_2/R_1} + \frac{1}{A_{V0}}. \tag{3}$$

For reasons that will be clearer later on, the resistances R_1, R_2, and R_D will be chosen in the range from a few hundred to a few thousand ohms. Moreover, to reduce the noise contribution from the diodes when operating in the forward region, the largest possible bias current should be set. In operating point A of Fig. 4, with no current flowing through the diodes, the differential resistance r_D is on the order of a few hundred kilohms or more, and the condition in (3) is not met (the system is unstable); in the operating points B, with the target bias current for the diodes on the order of a few milliamperes, r_D is on the order of a few ohms, and system stability is obtained. Let us now assume that at system turn on the output voltage is 0 (equilibrium point A). Because of instability, the output voltage will start drifting until either a stable equilibrium point or system saturation is reached. If the output voltage starts drifting toward more and more positive values, then the stable operating point B is reached; if the output voltage starts drifting toward negative values, then the evolution will stop when negative saturation is reached at the output of the OA. We are clearly interested in the first situation, and as it will be discussed later on, we can modify the circuit in such a way as to insure that, after turn on, the operating point B is reached. The output voltage corresponding to the operating point B depends on the number N of diodes in series and on the ratio R_2/R_1, and can be obtained by solving the following nonlinear system:

$$\begin{cases} \frac{V_O - NV_D}{R_D} = I_0\left(e^{\frac{V_D}{V_T}} - 1\right) \\ V_O = NV_D\left(1+\frac{R_2}{R_1}\right). \end{cases} \tag{4}$$

In (4), I_0 is the saturation current of each diode, and $V_T = KT/q$ (K: Boltzmann constant; T: absolute temperature; q: electron charge). In our design, we employ low-noise diodes obtained from a proper connection of low-noise SSM2220 bipolar junction transistor (BJT) transistors (the emitter is the diode anode, whereas the collector and base connected together are the diode cathode). For minimizing noise, according to the data provided by the manufacturer, a current on the order of a few milliamperes must flow through the transistors, and in this condition, the voltage drop across each diode is about 0.65 V, largely independent of the actual value of the current. By a proper selection of N and of the ratio R_2/R_1, any desired output voltage can be obtained.

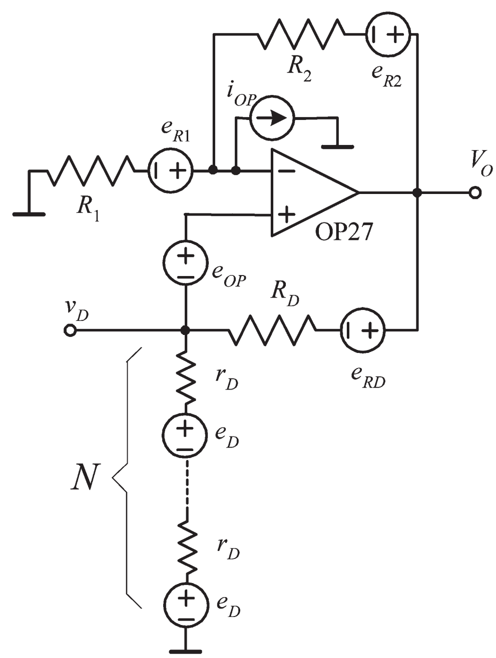

Fig. 5. Equivalent small-signal circuit for the evaluation of the output noise. All relevant noise sources are shown in the figure. Reprinted with permission from C. Ciofi, G. Scandurra, and G. Cannatà, "A new circuit topology for the realization of low noise voltage references", *Proceedings of the 20th International Conference on Noise and Fluctuations* (*ICNF* 2009), Pisa, Italy, 14–19 June 2009, 599–602 Copyright 2009 American Institute of Physics.

The estimation of the output noise of the system can be carried out with reference to the small-signal equivalent circuit in Fig. 5, where $r_D = V_T/I_D$ represents the differential resistance of each diode, and e_D is the equivalent voltage noise source introduced by each diode. Because of the very low value of r_D (r_D is on the order of a few ohms for biasing currents on the order of a few milliamperes), the equivalent input current noise source at the noninverting input of the OA has been neglected since its effect is very small compared with other sources of noise. Assuming a virtual short circuit between the inputs of the OA and assuming that all noise sources are uncorrelated, we can estimate the output power spectral density S_{VO} as in (5), shown at the bottom of the page, where S_{RX} is the power spectral

$$S_{VO} = \frac{S_{R2} + \left(S_{R1} + S_{IOP}R_1^2\right)\left(\frac{R_2}{R_1}\right)^2 + S_{OP}G^2 + S_{RD}\left(\frac{Nr_DG}{R_D+Nr_D}\right)^2 + NS_{eD}\left(\frac{R_DG}{R_D+Nr_D}\right)^2}{\left(1-\frac{Nr_DG}{R_D+Nr_D}\right)^2} \quad G = 1+\frac{R_2}{R_1} \tag{5}$$

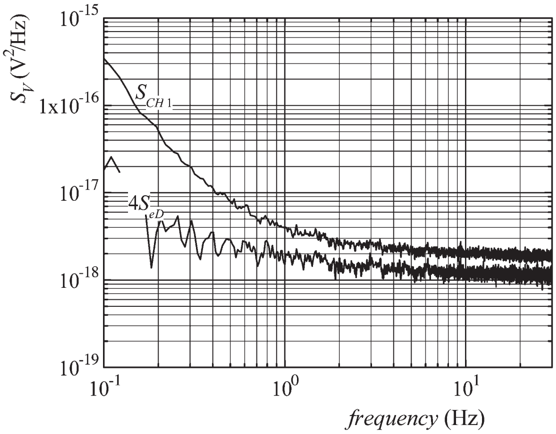

Fig. 6. Voltage noise across four diodes in series with a 1-mA bias current ($4S_{eD}$). Cross correlation between the output of two low-noise amplifiers connected to the output of the system was used for estimating the noise produced by the diodes. The equivalent input noise of one of the amplifiers during measurement is shown in the figure (S_{CH1}).

density of the noise source e_{RX} associated with the resistance R_X, S_{IOP} is the power spectral density of the equivalent input current noise i_{OP}, S_{OP} is the power spectral density of the EIVN source e_{OP}, and S_{eD} is the power spectral density of each of the noise sources e_D associated with each diode. It must be noted that it is not possible to estimate S_{eD} starting from the input equivalent noise sources reported in the data sheet as they are not physical noise sources but just fictitious sources that allow correct noise calculation only in specific circuit configurations. When a transistor is employed as a diode (with the base and the collector terminals shorted together), it is expected that the white noise component S_{eDW} of S_{eD} coincides with that due to shot noise, that is,

$$S_{eDW} = 2qI_D(r_d)^2 = \frac{2qV_T^2}{I_D}. \tag{6}$$

As far as the $1/f$ component of S_{eD} is concerned, it must be determined experimentally. This is not an easy task in the case of the SSM2220 because of the very low level of noise that needs to be determined at very low frequencies. For performing reliable noise estimation, we resorted to the circuit in Fig. 1, where the solid-state reference was replaced by a high-capacity lead-acid 12-V battery to not introduce noise. An excess noise-free 10-kΩ resistor was used for biasing a series of four diode-connected SSM2220. The bias current was 1 mA, and the expected white noise (shot noise) at the output was on the order of 1 nV/$\sqrt{}$Hz. For this reason, we resorted to cross correlation for a reliable estimation of the output noise [12]. Two JFET input very low noise preamplifiers [13] were connected in parallel to the output of the test circuit and spectra, and cross-spectrum estimation was performed by resorting to a computer-based spectrum analyzer employing a National Instruments PCI-4451 two-channel dynamic signal analyzer board. The results of the measurements are reported in Fig. 6. The cross-spectrum averaging time was about 3 h, and as it can be noted, the $1/f$ noise component becomes important below a few hertz. Each diode contributes for 1/4 of the total noise power. As far as S_{OP} is concerned, in the case of the OP 27, it is on the order of 16, 5, 3.3, and 3 nV/$\sqrt{}$Hz at the frequencies $f = 0.1$, $f = 1$, $f = 10$ Hz, and $f > 100$ Hz, respectively. Therefore, for values of N on the order of a few units, the noise introduced by the OA at very low frequencies is dominant with respect to that introduced by the diodes. As an example, for $f < 1$ Hz, and assuming a diode current larger than 1 mA, $S_{OP} > 50\ S_{eD}$. The contribution of S_{IOP}, for a fixed value of G, depends on the value of the resistance R_1. From the typical values of S_{IOP} for the OP27, it can easily be verified that the contribution of S_{IOP} in (5) can be neglected with respect to the contribution of S_{OP} provided that R_1 is significantly less than 1 kΩ. To minimize noise at very low frequencies, metallic film or wire-wound excess noise-free resistors must be employed. This is particularly important for the resistors R_1 and R_2 that, because of the conditions for minimizing the contribution of S_{IOP}, may be required to sustain currents on the order of several milliamperes. If we also assume that $Nr_D \ll R_D$ and that, as it will be clearer in the following, G is close to 1, then also the contribution by S_{RD} can be neglected, and taking into account all the foregoing observations, (5) can be simplified as follows:

$$\begin{aligned} S_{VO} &= S_{R2} + S_{R1}\left(\frac{R_2}{R_1}\right)^2 + S_{OP}G^2 + NS_{eD}G^2 \\ &= 4KTR_2G + (S_{OP} + NS_{eD})\,G^2. \end{aligned} \tag{7}$$

The parameters G and N are not independent of one another because they set the desired output voltage according to (4). As we have noted before, assuming that the voltage drop across each diode is known and essentially independent of the detailed bias conditions, we have

$$G = \frac{V_O}{NV_D} \tag{8}$$

and, therefore, (7) becomes

$$S_{VO} = \frac{1}{N}\left[4KTR_2\frac{V_O}{V_D} + \left(\frac{S_{OP}}{N} + S_{eD}\right)\left(\frac{V_O}{V_D}\right)^2\right]. \tag{9}$$

From (9), it is apparent that, as far as the output noise is concerned, it is convenient to select N as large as possible with the limiting condition that, since $G > 1$, N must be less than V_O/V_D. Indeed, a larger N also results in a lower R_2, thus further contributing to a reduction of the noise in (9). It must be noted, however, that (9) has been obtained in the assumption that Nr_D is much lower than R_D. Since from (4)

$$R_D = \frac{V_O - NV_D}{I_D} \tag{10}$$

we have

$$\begin{aligned} \frac{R_D}{Nr_D} \gg 1 &\Rightarrow \frac{V_O - NV_D}{I_D} \times \frac{I_D}{NV_T} \\ &= \frac{V_O - NV_D}{NV_T} \gg 1 \Rightarrow N \ll \frac{V_O - NV_D}{V_T} \end{aligned} \tag{11}$$

that is, N should be such that the difference between the desired output voltage and the total voltage drop across the series of N

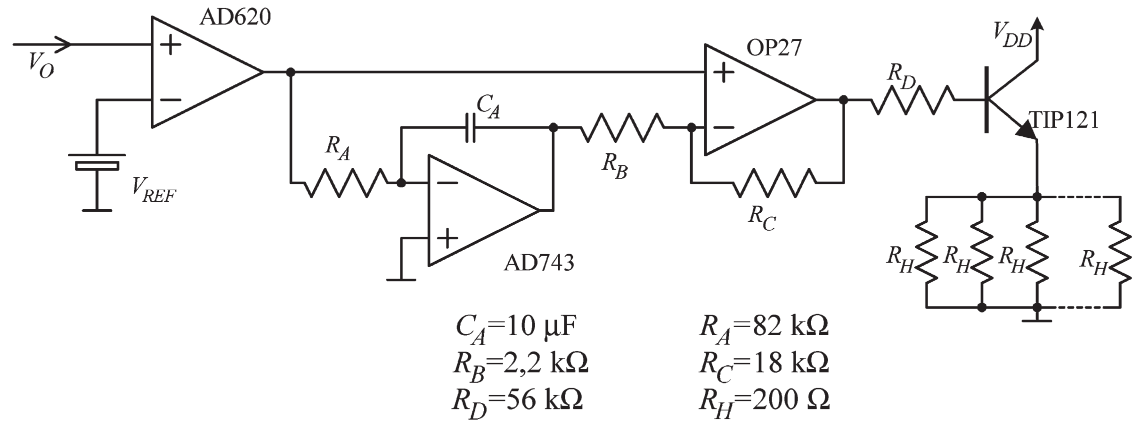

Fig. 7. Complete schematic of the temperature control system employed for reducing the temperature dependence of the output voltage of the new low-noise reference.

diodes remains several times larger than the thermal voltage V_T (25.9 mV at room temperature).

As an example, assume that we want to design a 5-V voltage reference. With a bias current on the order of a few milliamperes, the voltage drop across each diode is about 0.65 V at room temperature. According to (8), the maximum value of N for satisfying the condition $G > 1$ is 7. Unfortunately, with $N = 7$, the condition in (11) is not satisfied (7 cannot be assumed to be much less than 17.35). It is, however, sufficient to set $N = 6$ for satisfying (11): in this case, we would have $6 \ll 42$. In any case, by resorting to the complete expression in (6), one can refine the initial choice by verifying the level of noise that can be obtained with lower or higher values for N. According to (9), with R_2 on the order of 100 Ω, the most important contribution to noise comes from S_{OP} (5 nV/$\sqrt{\text{Hz}}$), resulting in an output of about 6 nV/$\sqrt{\text{Hz}}$ at 1 Hz. As a reference, the "low noise" 5-V solid-state voltage reference AD586 by Analog Devices is characterized by an output noise of about 100 nV/$\sqrt{\text{Hz}}$ at 1 Hz, which is about 23 dB above that expected from the new voltage reference. These expected performances are confirmed by actual measurements on a prototype of the system, as it will be demonstrated in the next section.

While characterized by excellent noise performances, the new voltage reference, at least in the very simple form in Fig. 2, is not comparable to solid-state voltage references as far as stability versus temperature is concerned. The temperature coefficient K_{VD} of the voltage drop across a forward-biased silicon diode is on the order of -2 mV/°C. Therefore, for the output voltage V_O, we have

$$\begin{aligned}\frac{dV_O}{dT} &= \frac{d}{dT}\left[NV_D\left(1+\frac{R_2}{R_1}\right)\right] \\ &= K_{VD}N\left(1+\frac{R_2}{R_1}\right) = K_{VD}\frac{V_O}{V_D}. \qquad (12)\end{aligned}$$

According to (12), the output voltage temperature drift depends on the ratio between the output voltage and the voltage drop across each diode: it does not depend on the number N of diodes and on all the other circuit parameters. In the case of a 5-V reference, assuming as before $V_D = 0.65$ V, the voltage drift with temperature would be about -15 mV/°C (-3000 ppm/°C). When performing low-frequency-noise measurements, the device under test, the bias system, and the low-noise preamplifiers are usually enclosed in a strongly shielded box, inside which a quite stable environment needs to be created in terms of mechanical and thermal fluctuations. Therefore, the relatively large voltage drift with temperature may possibly be accepted in many cases.

It is, however, possible to significantly improve the temperature stability of the new voltage reference by adding a closed-loop temperature control system. A very simple approach can be followed assuming that a solid-state high-stability voltage reference is available, whose output voltage is equal to that desired at the output of the low-noise voltage reference. When designing the low-noise voltage reference, the circuit parameters are selected in such a way as to have an output voltage slightly higher than the nominal voltage at the highest room temperature at which we plan to employ the system. A simple integral proportional controller, such as that reported in Fig. 7, can be used to drive, by means of a medium-power metal–oxide–semiconductor field-effect transistor or BJT, a series of resistances that, once in close contact with the SSM2220 packages, act as heaters. The control loop behaves in such a way as to have, in ideal conditions, the SSM2220 devices operating at the temperature that is required for having $V_O = V_{\mathrm{REF}}$ at the input of the controller, regardless of the actual ambient temperature. As it will be shown in the next section, such a rather simple approach may result quite effective, as it allowed, in the case of a 5-V voltage reference, to reduce the temperature drift down to about 13 μV/K, which is less than 3 ppm/°C, without significantly degrading the noise performances.

III. Experimental Results

A 5-V very low noise voltage reference was designed according to the guidelines previously detailed. To insure that at turn on the operating point of the circuit is the point corresponding to situation B in Fig. 4, the circuit in Fig. 2 was modified as reported in Fig. 8. When power supply is applied to the

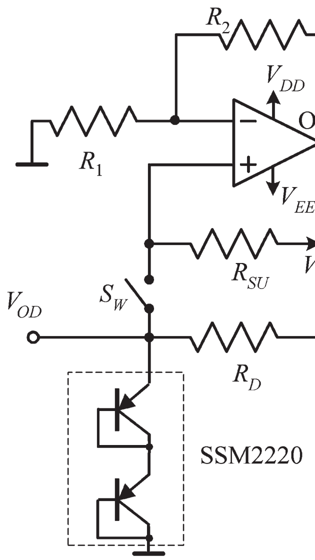

Fig. 8. Actual implementation of the new reference voltage. The presence of the high-value resistance R_{SU} together with the switch S_W allows bringing to operate in the proper equilibrium point at power on.

circuit, the switch S_W is open. In this situation, the circuit behaves as a noninverting amplifier, and the output voltage is close to the positive supply voltage because of the presence of the resistance R_{SU}. The value of R_{SU} is not critical, and a very large value (on the order of a few MΩ) can be used. Soon after the circuit has been turned on, the S_W is closed, and the original configuration in Fig. 2 is obtained, with the circuit evolving until the desired stable operating point is reached. The presence of the very large value resistor R_{SU} when the switch is closed can be neglected as it appears in parallel to the low equivalent resistances of the series of N diodes in the small signal equivalent circuit. Moreover, only a very small current flows through the closed switch S_W, and therefore, it does not introduce detectable levels of low-frequency contact noise. The measured voltage drop across each SSM2220 transistor connected as a diode was about 0.64 V at room temperature for a current between 3 and 4 mA. By following the design guidelines detailed in the previous paragraph, we selected $N = 6$ and $R_D = 400\ \Omega$. As we planned to employ the temperature stabilization system, we set the ratio R_2/R_1 in such a way as to obtain about 5.2 V at room temperature (27 °C). With a temperature coefficient of about -15 mV/°C, the target value of 5 V is expected to be obtained with the diodes operating at about 13 °C above room temperature (40 °C). From (5), we obtain $G = 1.350$, and therefore, $R_2 = 0.350\ R_1$. As we have noted before, R_1 must be as low as possible, the lower limit being set by the current supply capability of the output stages of the OP 27 that is on the order of 20 mA. With $R_1 = 300\ \Omega$, we have $R_2 = 105\ \Omega$ and a current flowing through R_1 of about 13 mA. The total current supplied by the OP 27 is, in the worst case $V_O = 5.2$ V, on the order of 17 mA (current through the resistances R_1 and R_2 and current through the diodes). Voltage noise measurements were performed at the output of the system, initially without any temperature control system. The system was supplied by two 12-V/6-Ah lead-acid batteries. It must be noted that, notwithstanding the relatively high supply current (on the order of 20 mA), much

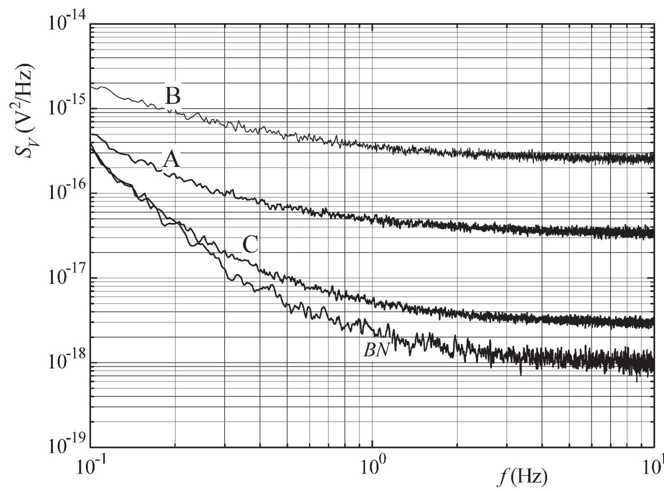

Fig. 9. Results of noise measurements on the prototype of a 5-V voltage reference realized according to the approach proposed in this paper. The background noise (BN) of the measurement system is shown in the figure. The BN was not subtracted from the measured spectra. Spectrum A is the noise at the output of the reference in the optimum condition $N = 6$. Spectrum B is the noise at the output when the system is realized with $N = 2$. Finally, spectrum C represents the voltage noise across the series of six diodes in the case corresponding to spectrum A.

smaller batteries could be used. Indeed, by employing 12-V/1.2-Ah lead acid batteries (such as Sonnenshein A512/1.2S) supplying 20 mA, a voltage drop of about 25 mV/h can be expected. Since the power supply rejection ratio of the OP27 is 120 dB, the effect on the circuit is equivalent to that of a voltage offset drift of the OA on the order of 25 nV/h. The results of noise measurements are reported in Fig. 9 (Curve A). The background noise introduced by the JFET very low noise preamplifier [13] was not subtracted from the measured spectra. As it can be noted, a noise level as low as 17, 7, and 6 nV/$\sqrt{\text{H}}$ is obtained at $f = 100$ mHz, $f = 1$ Hz, and $f >$ 10 Hz, respectively. In Fig. 9, the output noise of a 5-V low-noise reference designed with $N = 2$ is also reported (curve B). A significantly higher noise is observed, demonstrating the importance of the correct selection of the value of N. As it was expected from the discussion in the previous section, the noise level is set by the EIVN of OP27, suggesting that an even lower level of noise could be obtained should an OA with a lower EIVN be available for the design. Indeed, the very voltage drop across the series of N diodes can be regarded as a low-noise voltage reference, as in the case of the design discussed in [9]. In this case, a much lower level of noise is obtained as we do not resort to a highly noisy solid-state reference for biasing the diodes. The results of noise measurements across the series of N diodes are also reported in Fig. 9 (curve C). In addition, in this case, no background noise subtraction was performed. It can be noted that, at very low frequencies, the detected noise is actually coincident with the background noise of the amplifier, which means that the actual noise produced across the diodes is much lower. A detailed calculation of the noise that can be expected across the diodes could be performed by resorting once again to the equivalent circuit in Fig. 5.

The system was then tested while the temperature control system was in operation. An aluminum strip (thickness of 5 mm) was glued on top of the three aligned DIP8 packages

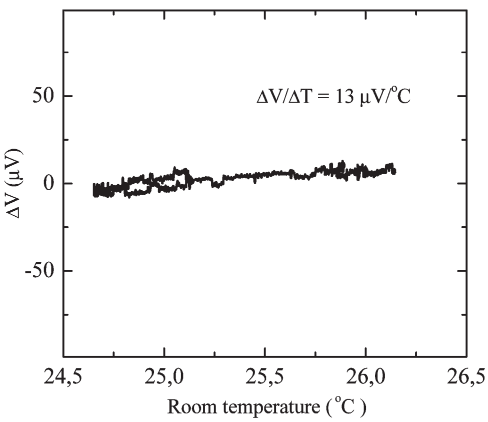

Fig. 10. Plot of the difference between the actual output voltage and the nominal voltage (5 V) as a function of the ambient temperature during one day of continuous operation of the voltage reference while the temperature control system was active.

containing the six SSM2220. Three 200-Ω 1/4-W resistors (R_H in Fig. 7) were placed in equally spaced holes drilled in the aluminum strip parallel to the top surface of the DIP8 packages. The voltage reference was enclosed in a $10 \times 6 \times 3$ cm 4-mm-thick, aluminum box, which, in turn, was placed in a wooden box to improve isolation with respect to the environment. The controller and the solid-state voltage reference were placed in a separate box. A separate high-capacity battery (12 V/10 Ah) was used for supplying the TIP121 that is part of the temperature control system. At steady state, the total current supplied by the TIP121 to the resistors R_H that act as heaters was below 50 mA. A plot of the output voltage as a function of the room temperature during a measurement session lasting about one day is reported in Fig. 10, demonstrating that a temperature coefficient on the order of 13 μV/°C corresponding to about 3 ppm/°C is obtained. With the temperature control system on, we measured the power spectrum of the output voltage fluctuations. Such a spectrum is reported in Fig. 11 together with the spectrum measured without any temperature control system. As it can be noted, the output noise slightly increases at frequencies below 300 mHz, whereas it remains unchanged elsewhere. When comparing the new results obtained with the prototype described in this paper with those that were reported in [11], it is apparent that better noise performances have been obtained thanks to the more detailed analysis of the influence of all system parameters on the output noise. On the other hand, a worse temperature stability is measured (3 ppm/°C instead of 1 ppm/°C). This difference can be attributed to the fact that whereas in the case of the first prototype discussed in [11] a single SSM2220 IC in DIP8 package (containing two transistors) was used, in the case of the new prototype, three SSM2220 ICs had to be employed to optimize the noise performances. Therefore, while in the first case the temperature of a single package had to be controlled, in the new prototype, the geometry of the heater had to be modified to make thermal contact to three distinct DIP8 packages at the same time. This may have resulted in a nonuniform distribution of the heat transfer between the heater and each single package, thus contributing to worse temperature dependence performances.

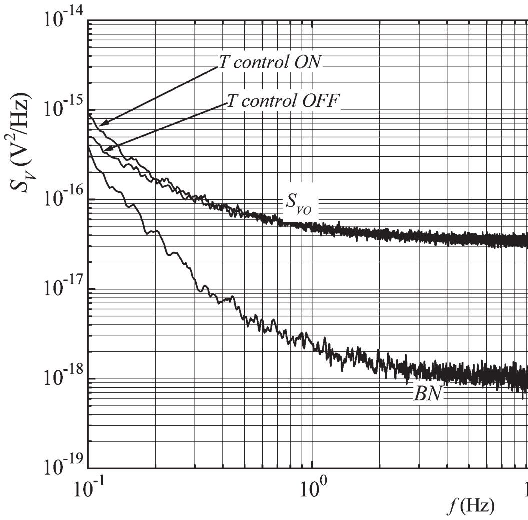

Fig. 11. Comparison between the output noise when the temperature control system is off (same as curve A in Fig. 9) and on. A slight increase in the noise can be observed at very low frequencies.

IV. Conclusion

In this paper, we have discussed a new approach for the design of very low noise voltage references. The new approach is based on the possibility of using the series of low-noise diodes biased in the forward region of operation as a low-noise voltage reference. By adding a proper temperature control system, a very low noise high-stability voltage reference can be designed. As an example, a 5-V voltage reference was designed by following the new approach that is characterized by a very low noise (26, 7, and 6 nV/$\sqrt{\text{Hz}}$ at 0.1, 1, and 10 Hz, respectively) with temperature stability on the order of 3 ppm/°C. A detailed analysis of the system from the point of view of the noise performances has revealed that the limiting factor for obtaining even lower noise levels is the equivalent input voltage source of the OA that is used as part of the self balancing bridge that provides for self biasing of the low-noise diodes. Therefore, better overall noise performances are expected if an OA with a lower equivalent input noise voltage is employed. As far as the temperature stability is concerned, measurements in different prototypes suggest that the geometry of the thermal coupling configuration does have an effect on the ultimate performances that can be obtained. While in the field of low-frequency noise measurements a stability of a few ppm/°C is more than adequate, the possibility of extending the application of the new circuit in the wider field of high-stability sources will require that a detailed investigation be made in the configuration of the heater-active device coupling system.

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