External-Reference Stabilized Current Source with Sub-ppm Stability

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***Abstract*—The noise and stability of a commercial current source is limited by the quality of components used for construction, such as the voltage reference chips, resistors, and power supplies. A state-of-the-art commercial current source typically exhibits a stability no better than parts in 10^7. In this paper, we present a way to implement a current source with "external" electrical references. This approach allows the current source stability to be decoupled from the noise characteristics of the main power supply circuit. A few parts in 10^8 stability is demonstrated here.**

***Index Terms*—Current measurement, Current supplies, Feedback circuit, Stability measurement.**

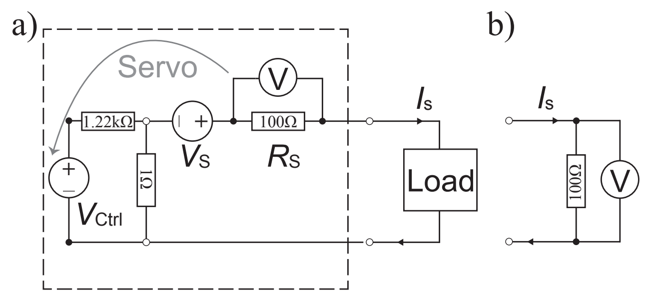

Fig. 1. The schematic of the current source and a possible scheme for the current measurements. (a) The main circuit with a voltage compensation function to stabilize the current. The feedback is represented by the grey line. (b) Current measurement based on an external 100 Ω resistor and a voltmeter.

I. Introduction

In the simplest form, a current source constitutes a constant voltage source across a precision resistor. Therefore, the stability of a current source ultimately depends on the stabilities of the voltage source and the resistor used.

Most commercial power supplies and meters adopt solid-state based voltage regulating integrated circuits. There is a wide variety of technologies underlying these monolithic voltage reference chips [1]. Space applications have motivated a series of performance evaluations on several of the best commercial voltage reference chips in the market [2], [3]. One of the most impressive reference chip is LTZ1000 based on the burried-zener construction. It is an oven temperature stabilized operating at 60 °C with a state-of-the-art thermal coefficient $\leq 5 \times 10^{-8}$/°C, a ≤ 1.2 $\mu\mathrm{V}_{\mathrm{p-p}}$ noise, and a ≤ 1 μV/month drift. The outstanding thermal characteristics originate from the opposing polarities in the thermal coefficients between the zener and the forward-biased base-emitter voltage of the adjacent transistor [3].

An ideal stable resistor should have a small sensitivity coefficient to the environment (e.g. vibration, temperature, humidity, and pressure) and a slow aging effect (drift rate). In addition, its characteristics should be independent of the load condition. Alloys of different compositions have been invented as the raw materials for the resistor construction [4]. Among them, Evanohm (a nickle-chromium alloy) is a class of material that exhibits a very low thermal coefficient. Recent advances in the thin-film technology allows the production of stable resistors based on the Evanohm alloy with state-of-art specifications of $\leq$ 0.1 ($\mu\Omega/\Omega$)/year drift and ≤ 0.14 ($\mu\Omega/\Omega$)/K thermal coefficient [5].

Developing a dedicated current source circuitry involving the stable voltage reference chip is cumbersome which involves ensuring the single-point ground connection and the minimization of thermal gradient across the printed circuit board layout. A simpler approach would be to integrate an existing system that already employs the voltage reference circuit and combine it with a stable resistor and a power supply to form a current source. In this external reference scheme, the noise characteristics at high and low frequency regimes can be decoupled permitting more flexibility in the current source design.

Here, we demonstrate an externally-referenced current source by combining the LTZ1000 voltage reference in a 8.5-digit multimeter and the Evanohm thin film resistor. We will illustrate the concepts in more details in the next section and present our progress in the performance evaluations of the current source.

II. Externally-referenced current source circuit

Figure 1(a) shows the generic schematic of the externally-stabilized current source. The power supply V_{s} provides a bias for the servo resistor R_{s} and the resistive load. The current I_{s} flowing through the circuit is subject to the temporal variation of the voltage output of V_{s}, the resistance of R_{s}, and the resistance of the load. Because all three instability sources are connected in series, the temporal fluctuation in the power supply and the resistance change of the load can be compensated by implementing a negative gain proportional-integral (PI) loop that stabilizes the voltage drop across the servo resistor R_{s}. In this voltage compensation scheme, the stability of the current source depends only on the relative stability between the servo resistor and the corresponding voltage measuring instrument.

The key for a proper stability validation is to have a current metering scheme with a stability the same (when the technological limit of the current source is already achieved) or better than the stability of the current source. One possible realization of the current measuring instrument is shown in Fig. 1(b).

In this experiment, all the voltage measuring instruments were 8.5-digit multimeters (Keysight 3458A) with LTZ1000 voltage reference chips inside. Both servo and load resistors were 100 Ω Evanohm thin-film type resistors (Alpha HRU-100). The power supply was a home-built 10-V voltage source.

Factors affecting the output range of this current source include the sourcing capability of the power supply, measuring range of the multimeter, and the power rating of the servo resistor. When the power supply was set at the maximum level 10 V, the current source could produce 50 mA output in the 100 Ω load.

III. Stability Evaluation

The setpoint voltage V_{Setpoint} of the PI feedback was set to 4.8047 V, corresponding to ≈ 48 mA through a nominally 100 Ω resistor. The error voltage V_{Error} was generated by $V_{\text{Error}} = V_{\text{Setpoint}} - V_{\text{Servo}}$. The mean of the error signal was -0.07 ± 0.56 nV, which was consistent with zero. The peak-to-peak correction voltage ΔV_{Ctrl} was 0.2 V for the whole measurement. This corresponds to a relative peak-peak current fluctuation of 39 ppm for the whole measurement spanning two weeks.

The peak-to-peak noise of the error signal across the 100 Ω servo resistor was $\approx$4 μV. This was dominated by the noise of the main power supply V_{s} instead of the coltral voltage source. As the result, the short-term noise of the observed current was 40 nA.

The offset between the setpoint and the measured current was -140 nA in this measurement scheme. Neglecting the difference in the resistances between the servo and the load resistors, the discrepancy in the internal voltage references between the two multimeters should be no more than 14 μV.

The noise spectrum and the Allan deviation of the current measured by the voltmeter are shown in Fig. 2. The white noise $\sqrt{S_w}$ was found to be 8.2 nA/$\sqrt{\text{Hz}}$. The best relative stability of the current was $\leq 3 \times 10^{-8}$ at a 100-s integration time. For integration times beyond 100 s, the current stability was dominated by the $1/f$ noise floor of the voltmeter. This stability sets the upper limit for the relative stability between the voltage references in the digital multimeters and the resistors (including both the servo and the load resistors). Assuming equal noise contributions from the servo and the load parts of the circuit, the intrinsic stability of the current source was determined to be $\leq 2.2\times10^{-8}$. An improvement in the stability beyond this level can only come from improving the voltage reference stability and a better temperature control (hence a better resistor stability). Current sources based on primary electrical voltage and resistance standards appear promising [6], [7].

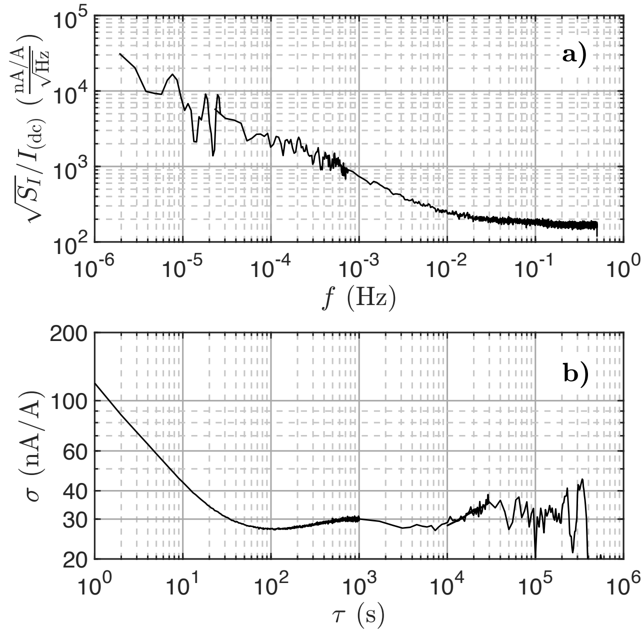

Fig. 2. (a) Noise spectrum and (b) Allan deviation of a 48 mA current measured by a LTZ1000 referenced voltmeter. The white noise density is determined to be 8.2 nA/$\sqrt{\text{Hz}}$. The stability is a few parts in 10^8.

IV. Conclusion

A current source with an external voltage reference and an external resistor reference was constructed. While the short-term noise was governed by the power supply of the current source, the long-term stability was dominated by the external references. A few parts in 10^8 stability limit was demonstrated. Further improvement in the stability beyond this level could come from better voltage reference and resistor stabilities.

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