Sylwester JABŁOŃSKI, Jarosław SIKORA[1]

Politechnika Lubelska, Katedra Automatyki i Metrologii (1)

doi:10.15199/48.2018.07.39

A current sink controlled by two reference voltages

Abstract. *This article describes the biasing circuit of a BJT operating as a current sink with two reference voltage sources, the first reference voltage controls the load current, while the second reference voltage controls the collector-base junction voltage of the BJT. As a result, the estimator of the correlation coefficient between the load current and the load resistance was obtained about four times smaller compared to the classical current sink.*

Streszczenie. *W artykule opisano układ polaryzacji tranzystora bipolarnego w konfiguracji źródła prądowego z dwoma źródłami napięć referencyjnych, z których pierwsze steruje natężeniem prądu obciążenia, drugie napięciem złącza kolektor-baza tranzystora. W rezultacie uzyskano estymator współczynnika korelacji między natężeniem prądu obciążenia i rezystancją obciążenia około cztery razy mniejszy w porównaniu do klasycznego źródła prądowego.* ***(Źródło prądowe sterowane dwoma napięciami referencyjnymi).***

Keywords: current source, effect of a base width modulation, automatic bias point control, load current standard deviation, correlation coefficient

Słowa kluczowe: źródło prądowe, efekt modulacji szerokości bazy, automatyczna regulacja punktu pracy, odchylenie standardowe natężenia prądu obciążenia, współczynnik korelacji

Introduction

Current sources, performed in different technology, are widely used in measurement applications such as electron-impact mass spectrometers, ionization gauges [1, 2], bio-impedance spectrometers [3-5] and other, for example, Hall effect instruments. Bipolar junction transistors (BJT) are characterized by good temperature properties and low costs. However, a one-BJT current source or sink cannot ensure a stable collector current as a function of a load resistance because of changes in a base current with changes in a collector-base junction voltage. This unwanted dependency is caused by the effect of a base width modulation, known as the Early effect [6]. The diagram of the basic BJT current sink (BJTCS), consisting of the transistor T_1, the emitter resistance R_E for a current feedback, the reference voltage source V_{ref1} and additionally, the operational amplifier OA_1, operating as an error amplifier, is shown in figure 1 in full lines.

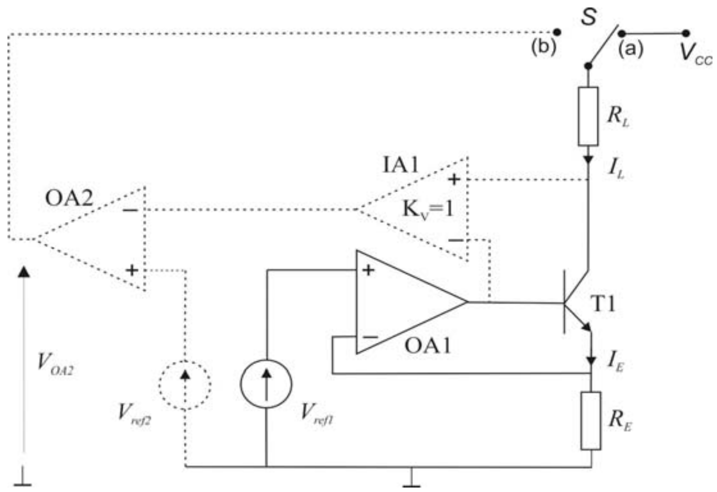

Fig. 1. A simplified diagram of the basic BJT current sink (full lines, switch *S*(a)) and with additions (broken lines, switch S_1(b)) introduced in this work.

The present additions marked in broken lines will be discussed later in this text. Assuming infinite input resistance and voltage gain for the operational amplifier OA_1 and consequently a virtual short circuit between its inputs (+ and −), the voltage drop across resistor R_E is equal to the reference voltage V_{ref1}, which leads to:

$$I_{E1} = \frac{V_{ref1}}{R_E} \tag{1}$$

The emitter current is maintained at a pre-set constant value, but the load current, I_L, is also dependent on the collector-base junction voltage [7]:

$$I_L = \frac{I_{E1}}{1 + \dfrac{1}{\beta_0 \exp(V_{CB1}/V_A)}} \tag{2}$$

where β_0 is a dc current gain factor of the transistor T_1 at V_{CB1}=0 and V_A is the “Early voltage”.

According to the diagram of the basic BJT current sink the collector-base junction voltage, V_{CB1}, may be written as follows:

$$V_{CB1} = V_{CC} - I_L R_L - V_{BE1} - I_{E1} R_E \tag{3}$$

where V_{BE1} is the base-emitter voltage of BJT_1.

The plot in figure 3 shows an example of the collector-base junction voltage as a function of the load resistance R_L at a constant load current value for the basic BJTCS. The measurements have been done for the transistor BF459 (Siemens), the operational amplifier CA 3140 (Intersil Corporation) and the reference voltage stabilizer REF 01 (Analog Devices). It can be seen while R_L increases V_{CB1} decreases and consequently, according to expression (2), the load current changes as shown in figure 4. The dependency of I_L on V_{CB} may be reduced by using an open loop system to control the collector-emitter voltage of the output BJT [8], but to achieve a satisfactory solution an automatic control of V_{CB} should be applied [9].

This work describes the BJTCS, which allows additionally setting and automatic controlling the collector-base junction voltage of the output BJT. Owing to that, the high load current quality has been obtained. The presented biasing circuit can be used optionally as a basic or novel BJTCS and is therefore highly suitable to quickly and easily compare considered current sinks (important for corresponding undergraduate laboratories). The biasing circuit is characterized by a simple and original design and a relatively low cost in terms of components, manufacturing and testing.

Fundamental concepts of the design

The complete schematic diagram of the present BJTCS is shown in figure 1, with the circuit upgrade shown in broken lines.

The switch S_1(b) connects the output of the operational amplifier OA_2 with the load resistor R_L. The collector-base junction voltage stabilizer is based on the operational amplifier OA_2. The resistor R_L, the collector-base junction of T_1 and the instrumental amplifier IA_1 form the negative feedback loop for OA_2. The IA_1 operates as a differential to single-ended collector-base junction voltage converter with a unity dc voltage gain. The operational amplifier, OA_2, compares the collector-base junction voltage, V_{CB1}, with the second reference voltage, V_{ref2}, to produce and amplify the error signal, which serves (V_{OA2}) to supply the current sink. In this way the power supply voltage, V_{OA2}, applied to the current sink is self-adjusted to keep the collector-base junction voltage, V_{CB1}, constant by means of a negative feedback loop. The reference voltage, V_{ref2}, is maintained across the collector-base junction of T_1:

$$V_{CB1} = V_{ref\,2} \qquad (4)$$

Assuming an infinite input resistance for the instrumental amplifier IA_1 and combining equations (1), (2) and (4), the load current, I_L, may written by the following expression:

$$I_L = \frac{V_{ref\,1}}{R_1\left(1+\frac{1}{\beta_0 \exp\left(V_{ref\,2}/V_A\right)}\right)} \qquad (5)$$

It is seen that the load current is controlled by two reference voltages V_{ref1} and V_{ref2}.

The output voltage of OA_2, which serves to supply the collector of the T_1, can be written as follows:

$$V_{OA2} = I_L R_L + V_{ref\,2} + V_{BET1} + V_{ref\,1} \qquad (6)$$

The expressions (1), (4) and (5) describe the T_1 bias point. It should be noted that a constant value of the collector-base junction voltage implies a stable electrical collector-base junction capacitance of BJT_1.

Circuit details

Most of the current sink details are shown in figure 2.

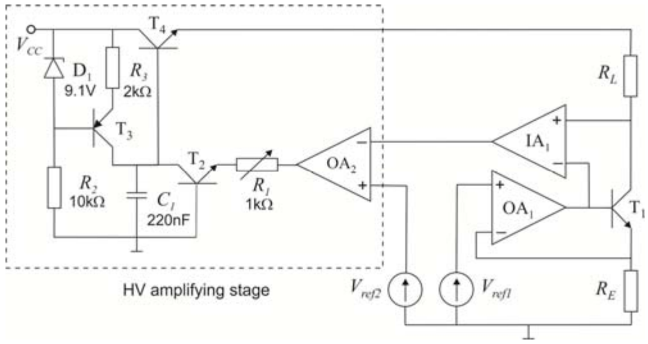

Fig. 2. A schematic diagram of the current sink. T_1, T_2 and T_4 are BF459 (Siemens); T_3 is BC393 (Siemens); OA_1, OA_2 are CA3140 (Intersil Corporation); IA_1 is INA 128 (Burr Brown); reference sources are based on the REF 01 (Analog Devices); V_{CC1}=125V/200mA; all integrated amplifiers are supplying from the voltage source +/−15V/200mA. The HV amplifying stage may be replaced by the HV operational amplifier, for example, PA 241 (Cirrus-Logic).

Because the output voltage from OA_2 is too low a high voltage amplifying stage was added. The output voltage of T_2 feeds the base of the T_4, which controls the emitter voltage of T_4 to supply the T_1. Transistor T_3, diode D_1, resistors R_2 and R_3 constitute a suitable current source to supply the collector of T_2 and the base of T_4. The reference voltages V_{ref1} and V_{ref2} control the emitter current and collector-base junction voltage of T_1, respectively. In our case, the current sink operates at V_{ref2} = 10V and V_{ref1} varies in the range from 0V to 2V. For satisfactory operation of the IA_1 (INA 128), the collector voltage of T_1 should be under 13V. The capacitor C_1 modifies the voltage gain of the high voltage amplifying stage to achieve a stable operation of the whole circuit.

Results and conclusions

In order to verify the presented idea the measurements of V_{CB1} and I_L were performed. Figures 3 and 4 show plots of the collector-base junction voltage of the T_1 and the load current, respectively, as a function of the load resistance for the current sinks considered above.

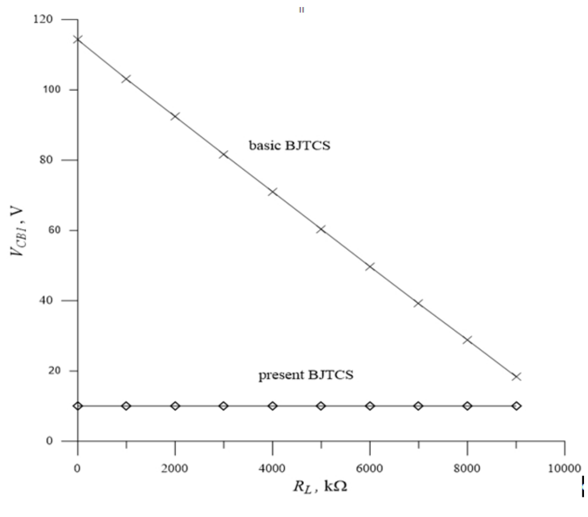

Fig. 3 Comparison of the two plots of the collector-base junction voltage, V_{CB1}, versus the load resistance, R_L.

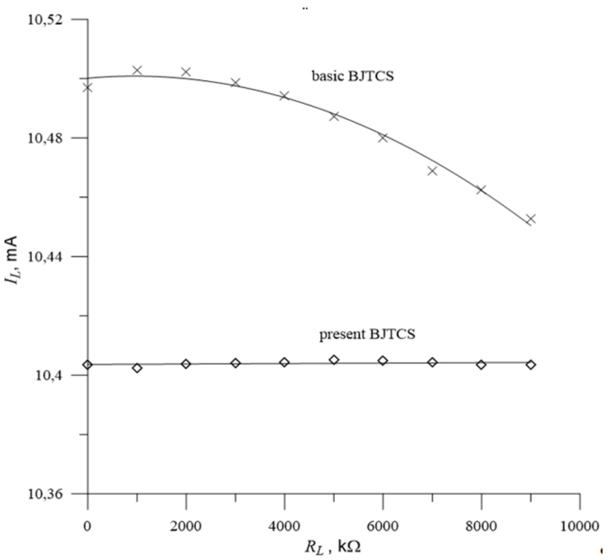

Fig. 4. Comparison of the two plots of the load current, I_L, as a function of the load resistance, R_L.

It is seen from these figures that the stabilized collector-base junction voltage, V_{CB1}, of the T_1 (figure 3) improves the load current quality as a function of the load resistance (figure 4). The present BJTCS can maintain I_L constant within 0.06% (it is a value of load current standard deviation in the full range of load resistance). The load voltage, in our case, is in the range from 0V to 93.636V.

The measurements were performed by means of digital multimeters, Agilent 34461A. The total current measurement error (including the reading error and the range error) is less than 0.030% over the full measurement range and the tolerance of the load resistance is less than 0.05%.

To compare the performance of the discussed circuits the estimator, r, of the correlation coefficient between the load current and the load resistance has been determined with the following formula:

(7) $$r(I_L, R_L) = \frac{\sum_{i=1}^{N}\left(I_{Li} - \overline{I_L}\right)\left(R_{Li} - \overline{R_L}\right)}{\sqrt{\sum_{i=1}^{N}\left(I_{Li} - \overline{I_L}\right)^2 \sum_{i=1}^{N}\left(R_{Li} - \overline{R_L}\right)^2}}$$

where: where $\overline{I_L}$, $\overline{R_L}$ are, respectively, average values of load current and load resistance and N is the number of measurement points.

The obtained values of r were 0.99 and 0.25 for the basic and novel current sinks, respectively.

The designed biasing circuit of BJT can be operated optionally as the basic or novel current sink (a choice can be realised with one switch), which can be utilized to quickly and easily study and compare their parameters, for this reasons it could be a useful supplement for corresponding undergraduate courses.

The advantages of the present BJTCS can be listed as follows:

(1) The percentage standard deviation of the load current is of 0.06% in the full range of the output voltage (0-93,6)V.
(2) The collector-base junction voltage of BJT_1 is kept at a pre-set constant value over the whole operating range.
(3) A constant value of the collector-base voltage allows a stable electrical collector-base junction capacitance to be maintained.
(4) The novel BJTCS is simple, convenient in operation and inexpensive.

Acknowledgment
This study was supported by the Lublin University of Technology under S-26/E/2017 Program.

Authors: *dr hab. inż. Jarosław Sikora prof. PL, Politechnika Lubelska, KATEDRA Automatyki i Metrologii, ul. Nadbystrzycka 38A, 20-618 Lublin,E-mail: jaroslaw.sikora@pollub.pl; mgr inż.Sylwester Jabłoński E-mail: sylwek_jab@poczta.fm*

REFERENCES

[1] Sikora J., Halas S., A novel circuit for independent control of electron energy and emission current of a hot cathode electron source *Rapid Commun. Mass Spectrom*. 25, (2011), 689–692
[2] Sikora J., Dual application of a biasing system to an electron source with a hot cathode *Meas. Sci. Technol*. 15, (2004), N10 - N14
[3] Jinzhen L., Xiaoyan Q., Mengjun W., Weibo Z., Gang L., and Ling L., The differential Howland current source with high signal to noise ratio for bioimpedance measurement system *Rev. Sci. Instrum.* 85, (2014), 055111
[4] Hayatleh K., Terzopoulos N., & Hart B. L., A very high output resistance current source *Meas. Sci. Technol*. 18, (2007), N9-N11 [5] Hayatleh K., Terzopoulos N., & Hart B. L., Designing a very high output resistance current source for medical applications *International Journal of Electronics*, 99, 12, (2012), 1739-1752
[6] Early J. M., Effects of space-charge layer widening in junction transistors *Proc. I.R.E.* 40, (1952), 1401-1406
[7] Hart Bryan L., Modeling the Early Effect in Bipolar Transistors, *IEEE Journal of Solid-State Circuits* SC-18, 1, (1983), 139-140
[8] Sikora J., Current source with controlled power supply voltage, Electron Technology Conference 2013, edited by P., Szczepanski, R., Kisiel, R. S., Romaniuk, Proc. of SPIE Vol. 8902, (2013), 89020Y
[9] Sikora J., System of the controlled bipolar current source, Patent PL 220502, WUP 10, (2015) [in Polish]