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THERMOCOMPENSATED DC SOURCES FOR CURRENT-MODE DIGITAL-ANALOG CONVERTERS

Sources of the reference voltage and current are the integral component of any electronic circuit. Especially important role sources of reference voltage and current play in analog circuits, many quantitative parameters of circuits operation depend on them. For instance, in analog-to-digital and digital-to-analog converters value of the full scale is determined by the reference source of voltage. Nowadays there exist many different approaches to the construction of D. C. sources circuits. Classic variant of reference voltage sources construction is the usage of the stabilitron and effects of Zener (tunnel) and avalanche breakdowns in it at the reverse-bias voltage. Zener breakdown occurs at the voltage of less than five volts and has negative temperature coefficient, avalanche breakdown occurs at higher voltages and has positive temperature coefficient. At the breakdown voltage in the range of five to eight volts its total positive voltage temperature coefficient (VTC) approximately equals negative voltage temperature coefficient (VTC) of the direct-biased diode. Sources of the reference voltage are determined by the bandgap voltage of the silicon, and provide good VTC at low supply voltages. To achieve thermal compensation in the circuit the matched transistors with the difference of the currents density, flowing across them, are used. Method of the reference voltage formation of the bandgap is attractive for the realization due to the comparative simplicity and low level of noise.The paper suggests new approach to the construction of the thermostable sources of the reference current on the base of the bipolar transistors using the voltage of the semiconductor bandgap and current mirrors. The given research contains circuit engineering analysis of the static characteristics of the proposed circuits of the thermocompensated bipolar DC sources of the circular type in the preset temperature range, principle of achieving thermal compensation are analyzed. Computer simulation of the static characteristics of the given reference current generators, such as current temperature drift as well as stabilization coefficient in case of the supply voltage change (loading capacity) is performed.

Key words: *circuit engineering modeling, thermostability, compensation, reference current generator.*

Introduction

In analog-to-digital and digital-to-analog converters the full scale value is determined by the reference source. Low level of noise and low voltage temperature coefficient of the output signal of reference source is very important for the performance and resolving power of the converters. Error of ±5 mV of the source of reference voltage (SRV) 5 corresponds to the absolute accuracy of ±0,1 % i. e., 10 bits. Temperature drift of SRV may create greater problem, than the absolute accuracy.

Relevance

Nowadays there exist numerous approaches to the construction of the circuits of DC sources [1 – 4]. The simplest diode SRV is current-controlled direct-bias diode (or transistor, connected as a diode). However, such circuit of SRV has many drawbacks: high voltage temperature coefficient (VTC), approximately -0,3 ррт/°С, sensitivity to loading and short flexibility of the output voltage (value of the output voltage belongs to the row with the step of 600 mV).

Another variant of SRV construction is the usage of stabilitron, far greater output voltage can be achieved in it. Zener breakdown occurs at the voltages of less than 5 V and has negative temperature coefficient, avalanche breakdown occurs at far greater voltages and has positive temperature coefficient. At the breakdown voltage in the range from 5 to 8 its total positive voltage temperature coefficient approximately equals negative voltage temperature coefficient (VTC) of the direct-bias diode. As a result, at certain offset current total VTC of the order of 100 ppt/°C is achieved. But the best combinations of VTC fall on the non-standard voltage (for instance, 6.2 V). Stabilitron- based

RVS must operate from the voltage source, which exceeds 6 V, that is an obstacle for their application in the systems with the supply voltage 5 V and less. Besides, stabilitron-based RVS with small VTC, have large noise level, that is result of the breakdown mechanism.

Development of the sources of low (< 5 V) reference voltage, based on the band-gap voltage of the silicon [1 – 4] led to the emergence of various integrated circuits, which provide good VTC at low supply voltages. In the circuit, for achieving thermal compensation, matched transistors with the difference in the current density, flowing across them, are used. Method of the bandgap reference voltage formation is attractive for the realization in the integrated circuits, due to its comparative simplicity and lack of stabilitrons and noise, connected with them. These RVS operate at low supply voltages (less than 5 V). That is why, the subject of the paper, where the possibilities of the construction of thermocompensated DCS of the circular type are analyzed, is relevant.

Objective of the paper – is to suggested and analyze new methods of the construction of the circuits of thermocompensated direct current sources (DCS) of the circular type of the enhanced thermostability, using the properties of the semiconductor energy gap width.

Tasks

1. Suggest and analyze new methods of construction of thermocompensated bipolar DCS of the circular type, using the properties of the semiconductor energy gap width.
2. Perform circuit engineering analysis of the static characteristics of the suggested circuits of thermocompensated bipolar DCS of the circular type in the preset temperature range.
3. Perform computer modeling of the static characteristics of the given reference current generators, such as temperature drift of DCS current and stabilization coefficient in case of the change of the supply voltage (loading capacity).

Tasks solution

Scheme of DCS with the simple compensation of the temperature drift is shown in Fig. 1a [5 – 6]

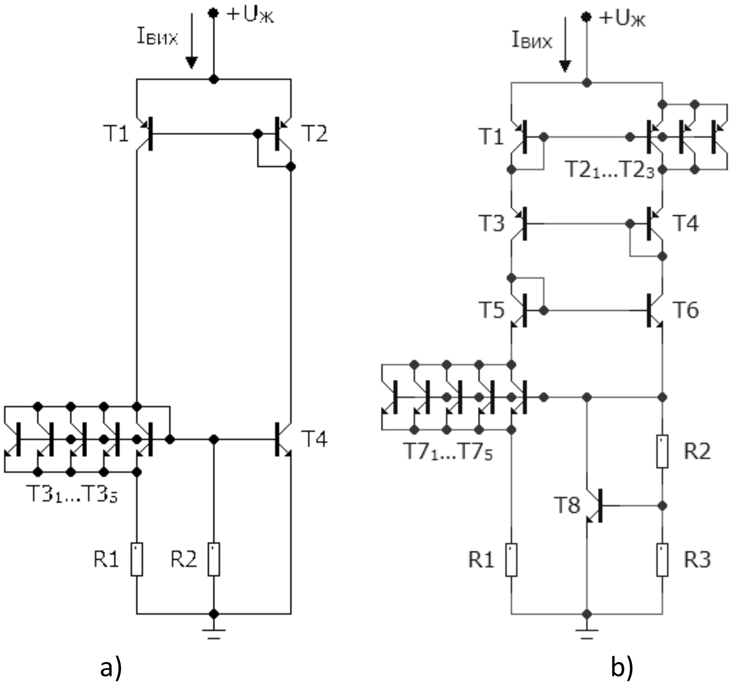


Fig. 1. Schematic diagram of DCS: a) with simple compensation of the temperature drift; b) with the improved compensation of the temperature drift

We will describe the operation of the circuit, presented in Fig. 1a. Current flows across the transistor T4 by means of the current mirror on the transistors T1 and T2 and is transferred to parallel connected resistor R2, the circuit is composed of serially connected resistor R1 and a group of transistors $T3_{1-5}$.

Transistors $T3_i$ are connected in parallel to decrease the current, flowing across them. Thus, the current, flowing across each transistor $T3_i$, will be approximately ten times less than the current, flowing across the transistor T4. Dependence of the voltage on p-n junction on the current, flowing across it is determined by the formula [7]:

$$for\ I > I_T \quad U \approx \frac{k \cdot T}{q} \cdot \ln\left(\frac{I}{I_T}\right). \tag{1}$$

Value of the thermal current is set by the formula [7]:

$$I_T = I_{TO} \cdot T^3 \cdot e^{-\frac{q \cdot E_G}{k \cdot T}}, \tag{2}$$

where k – is Boltzman constant, q – is the charge of the electron, T – is the absolute temperature, I_T – is thermal current of p-n junction. I_{T0} – is certain constant, E_G – is the voltage of the semiconductor bandgap.

Substituting this value into the previous expression we obtain:

$$U = \frac{k \cdot T}{q} \cdot \left(ln(I) - ln(I_{TO}) - 3 \cdot ln(T)\right) + E_G. \tag{3}$$

We will find the derivative from this function that determines the rate of the voltage change with temperature (on the condition of the direct current across p-n junction):

$$for\ I \approx const \quad \frac{dU}{dT} = \frac{k}{q} \cdot \left(\ln(I) - \ln(I_{TO}) - 3 \cdot \ln(T) - 3\right). \tag{4}$$

The derivative will have the negative meaning (voltage on p-n junction decreases with the increase of the temperature) and proceeding from this formula it can be seen that the smaller current flows across p-n junction the smaller the voltage is (voltage will decrease more rapidly).

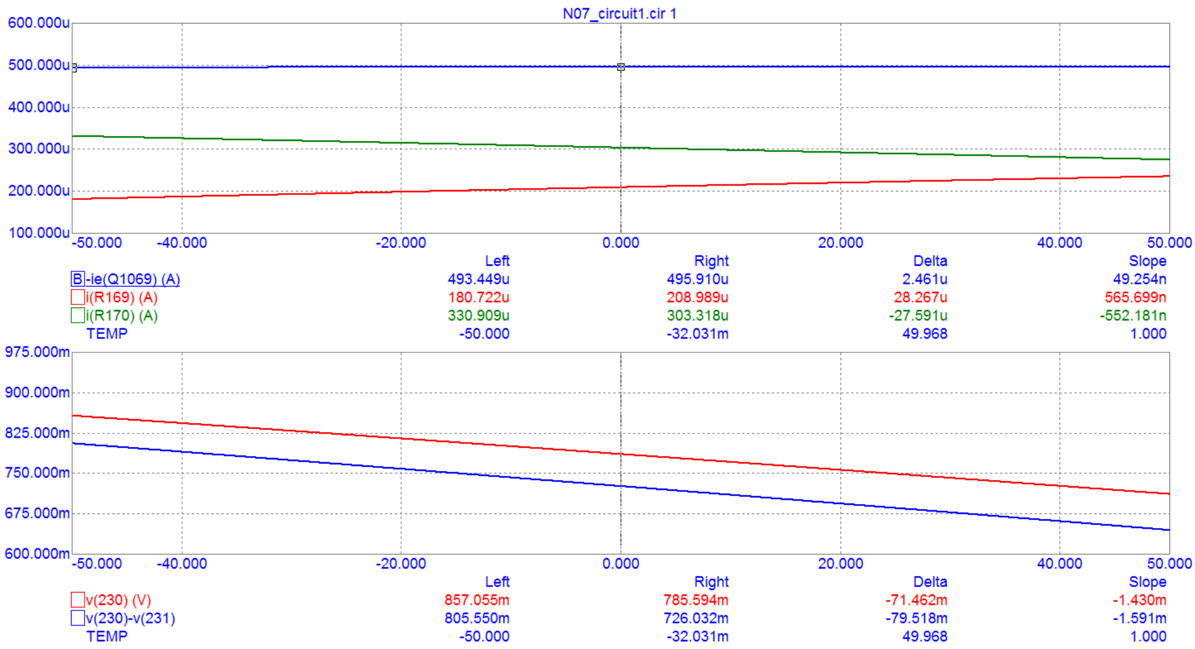
When thermal compensation is achieved, the current across the transistor T4 will remain constant. It follows that the voltage at the resistor R2 and current across it will decrease with the temperature increase and will be set by the formula (3). As the voltage at the emitter junctions of the transistors $T3_i$ will decrease more rapidly (on the condition of unchangeable flowing current), than at the emitter junction of the transistors T4 due to smaller flowing current (as it was noted earlier), then the voltage at the resistor R1 and current across it will increase:

$$U_{R1} = U_{beT4} - U_{beT3} = \frac{k \cdot T}{q} \cdot \left(ln(I_{T4}) - ln(I_{T3})\right) \tag{5}$$

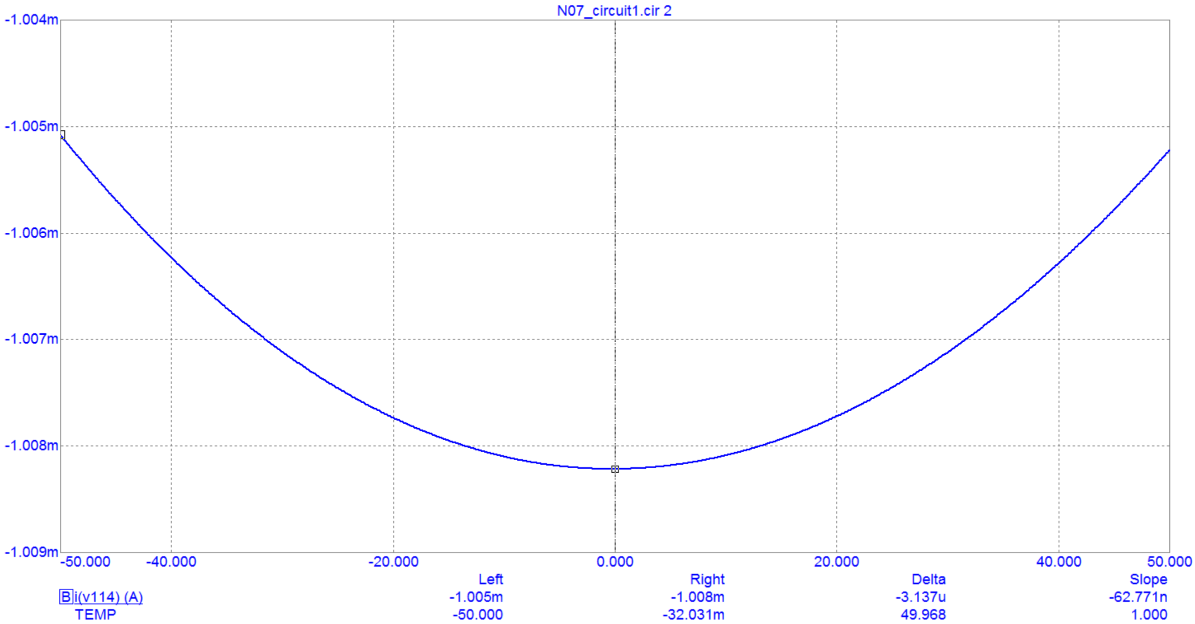
Hence, the decrease of the current across the resistor R2 with the increase of the temperature will be compensated by the increase of the current across the resistor R1, and at corresponding selection of the resistors R1 and R2 total current of the current source will not depend on the temperature. Having selected the nominals of the corresponding resistors the complete compensation can be achieved

Figs. 2a and 2b present the results of the circuit modeling in MicroCap 11 program, in the upper part of the Fig. 2a the changes of the currents, flowing across the resistors R1, R2 and transistor T4 are shown, in the bottom of the Fig. 2a changes of the voltage across p-n junctions of the transistors T4 and $T3_i$ are shown. Fig. 2b shows the dependence of the output current of DCS on the temperature, maximum temperature drift is 3 μA per 100°C (0.03 ppm/°C).

This circuit enables to perform only simplest compensation of the temperature drift of DCD (as it follows from (4), (5) with the increase of the temperature the voltage decrease on R2 will accelerate and the decrease of the voltage across R1 remains approximately constant). Besides, this circuit is characterized by low output resistance (approximately 13 кOhm).



a)



b)

Fig. 2. DCS with simple compensation of the temperature drift: a) currents and voltage changes across p-n junctions of the circuits elements; b) dependence of the output current on the temperature

Schematic diagram of DCS with the improved compensation of the temperature drift is shown in Fig. 1b. It operates in the following way. Current flows across the resistor R1 and transistors $T7_{1\text{-}5}$ by means of the current mirror on the transistors T1 and $T2_{1\text{-}3}$, and is transferred to parallel connected transistor T8 and the circuit, consisting of the of the resistors R2 and R3, connected in series, resistive divider, formed by these resistors. Transistors $T7_i$ are connected in parallel to decrease the current, flowing across them. Transistors $T3_j$, connected in parallel, set the coefficient of the current mirror reflection one to three (1:3). Thus, the current, flowing across each transistor $T7_i$ is approximately ten times smaller than the current, flowing across the transistor T8. Cascodes on the transistors T3, T4 and T5, T6 serve for the determination of the output voltage of the circuit.

If the thermal compensation is achieved, the current across the resistor R1 and transistors $T7_i$ will remain constant. It follows that the voltages on the transistors $T7_i$ bases will decrease with the temperature growth. Voltage of the base of the transistor T8 will be:

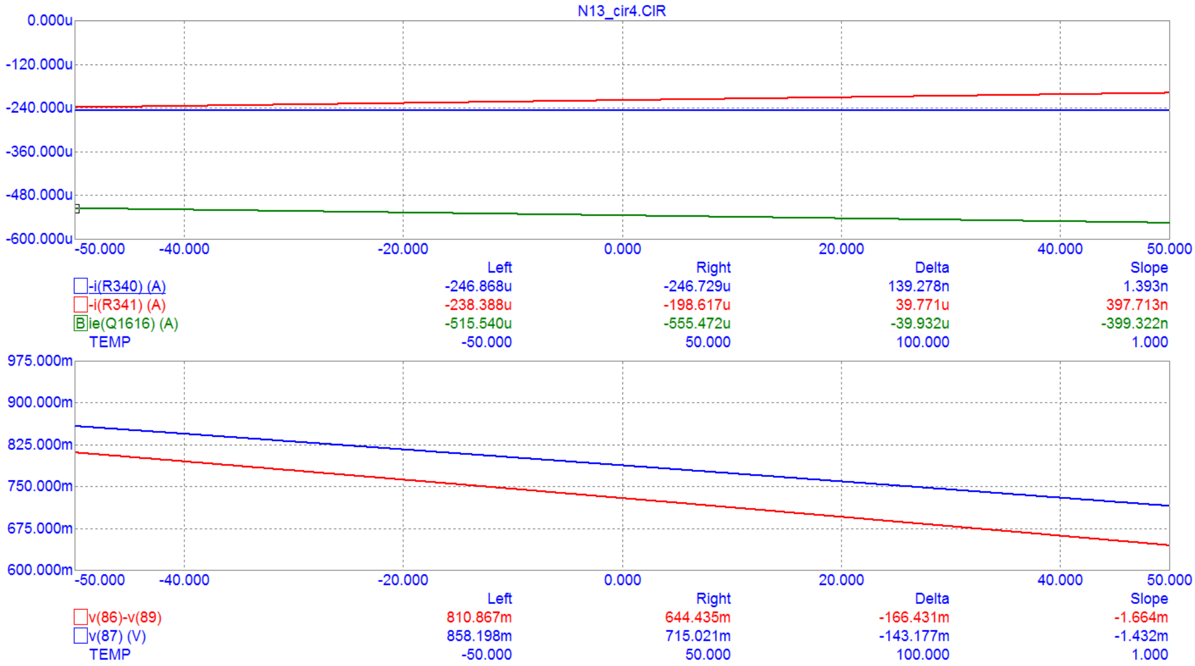
$$U_{R3} = \frac{R3}{R2+R3} \cdot \left(R1 \cdot n \cdot I_{T7} + \frac{k \cdot T}{q} \cdot \left(ln(I_{T7}) - ln(I_{TO}) - 3 \cdot ln(T) \right) + E_G \right) \tag{6}$$

As it can be seen from the above- mentioned formula only one component of the voltage decreases with the temperature. At the same time the rate of voltage decrease at the base of the transistor T8 will be less than the rate of voltage change at the p-n junction of transistor T8 base-emitter on the condition of unchangeable current across it (3). As a result, the current across the transistor T8 will grow with the temperature increase. Thus, decrease of current, flowing across the resistors R2 and R3 with the increase of the temperature will be compensated by the increase of current across the transistor T8, and under the corresponding fitting of the nominals of all the resistors the total current of the current source will not depend on the temperature .

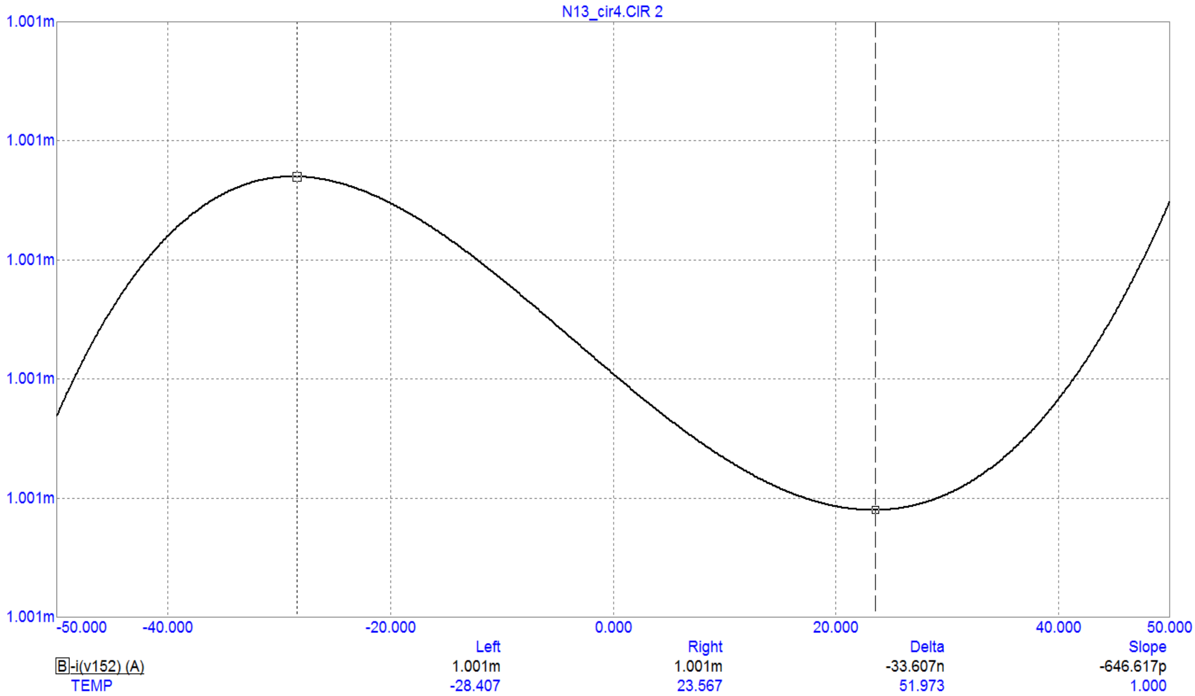
Figs. 3a and 3b present the results of the circuit modeling in MicroCap 11 program. In the upper part of Fig. 3a currents changes across the resistors R1 and R3, transistor T8 are shown, in the bottom part of Fig. 3a voltage changes across p-n junctions of the transistors T8 and $T7_i$ are shown. Fig. 3b presents the dependence of the output current of DCS on the temperature, maximum temperature drift is 33 nA per 100°C (0.0003 ppm/°C).

This circuit enables to perform more complete compensation of the temperature drift of DCS (as it follows from (4) (6) with the temperature increase, the rate of voltage decrease on the divider R2, R3 will accelerate but the rate of voltage increase on T8 will also accelerate). Thus, the compensation of the current decrease acceleration across the resistive divider on R2 and R3 can be achieved by accelerating the current increase across T8. This circuit is characterized by higher output resistance (approximately 505 кOhm) by means of introducing cascodes on the transistors T3, T4 and T5, T6.

DCS circuit with perfect compensation of the temperature drift is shown in Fig. 4a. This circuit operates similarly the previous one. Current flows across the resistor R4 and transistors $T11_{1\text{-}5}$ on the condition of achieving thermal compensation remains constant. It follows that the voltage of the bases of the transistors $T11_i$ decreases with the temperature increase. The voltage will arrive on the resistive divider, formed by the resistors R2 and R3. These resistors set the operating point of the transistor T12. Transistors $T11_i$ are connected in parallel to decrease the current, flowing across them. As in the previous case (6) rate of voltage decrease on the base of the transistor T12 will be less than the rate of voltage change on the p-n junction of base-emitter of the transistor T12 on the condition of the unchangeable current across it in accordance with (3). This will result in current increase across the transistor T12 with the temperature growth. Current of the transistor T12 by means of the current mirror on the transistors T1, T2 and T10, T9 will be sent to the resistive divider, formed by the resistors R2 and R3. As the current mirror is not absolutely symmetric, then the current across the transistors T10 and T9 will slightly differ (it will be smaller across T10) and, correspondingly, voltage drops at their emitter p-n junctions and the temperature change rate of the latter will differ. As a consequence, the current, dependent on the temperature will flow across the resistor R1. Cascodes on the transistors T3-T5 and T6-T8 serve for the increase of the output resistance of the circuit.



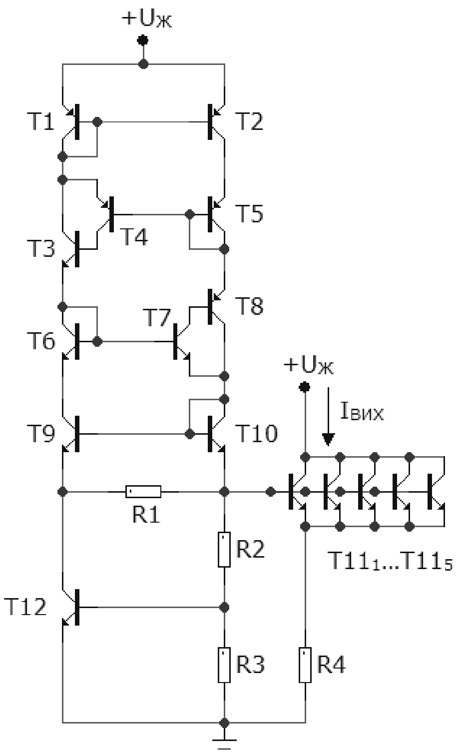
a)



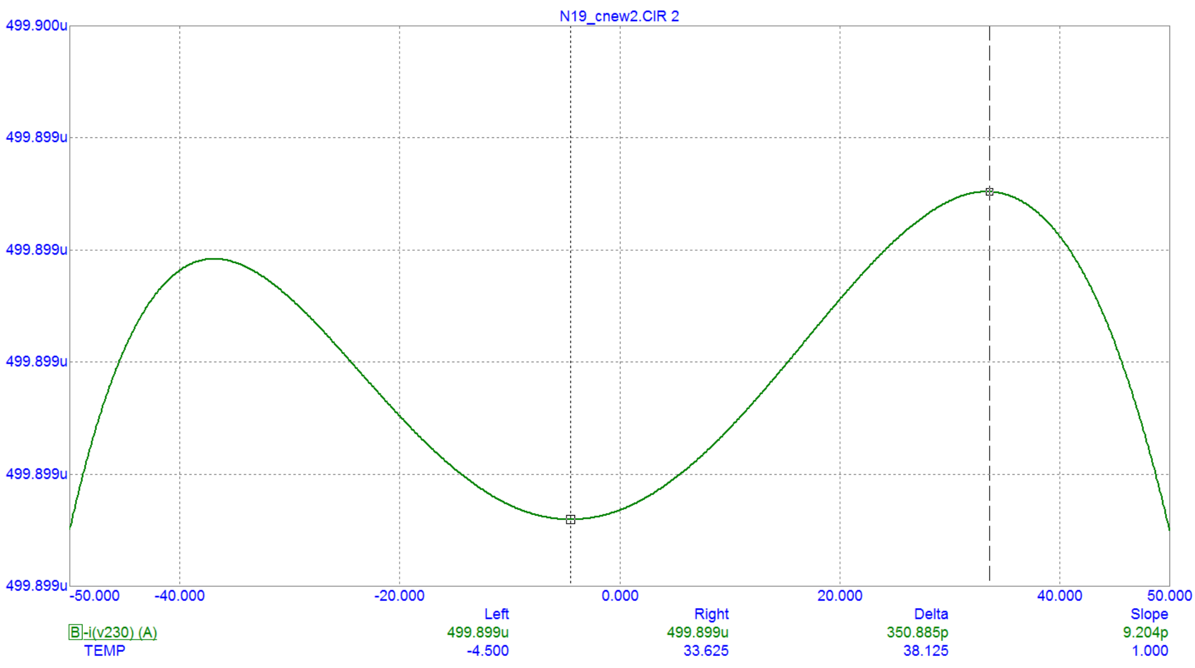
b)

Fig. 3. DCS with the improved compensation of the temperature drift: a) at changes of currents and voltages across p-n junctions of the circuit elements; b) dependence of the output current on the temperature

Fig. 4b shows the dependence of the output current of DCS on the temperature, maximum temperature drift is 350пA per 100°C (0.000003 ppm/°C). This circuit enables to perform almost complete compensation of the temperature drift of DCS. Also this circuit is characterized by higher output resistance (approximately 7.8 Mohm).



a)



b)

Fig. 4. DCS with very high compensation of the temperature drift: a) circuit diagram ; b)dependence of the output current on the temperature

The given research describes the methods of the construction of thermocompensated bipolar circular type DCS , using the properties of the semiconductor bandgap width and current mirrors, with different stages of thermal compensation from 0.03 ppm/°C for the simplest circuit, Fig. 1a to 0.000003 ppm/°C for the circuit with the best thermal compensation, Fig. 4a. The possibility of increasing the loading capacity of DCS as a result of using cascodes in the circuits of up to 505 кOhm, and using the cascodes with the composed transistors up to 7.8 Mohm is shown. But the cost of thermal compensation improvement is higher requirements to the accuracy of certain resistors of the circuits: 1 % – 0.1 % for the circuit in Fig. 1a, 0.01 % – 0.001 % for the circuit in Fig. 1b, 0.0001 % – 0.00001 % for the circuit in Fig. 4a.

Conclusions

1. New methods of construction of thermocompensated bipolar circular type DCS, using the properties of the semiconductor bandgap width and current mirrors with different stages of thermal compensation were suggested.

2. Circuit engineering analysis of the static characteristics of the suggested circuits of thermocompensated bipolar circular type DCS has been performed. Principles of their operation and means, as a result of which thermal compensation is achieved as well as means of increasing loading capacity of DCS are described.

3. Computer modeling of the static characteristics of the given DCS such as temperature drift of the current (from 0.03 ppm/°C for the simplest circuit to 0.000003 ppm/°C for the circuit with the highest thermal compensation), stabilization factor in case of supply voltage change (loading capacity), which is from 13 кOhm for the simplest realization to 7.8 Mohm was performed.

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