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CONSTRUCTION OF THE MATHEMATICAL MODELS OF OPTIC-FREQUENCY TEMPERATURE SENSORS ON THE BASIS OF STRUCTURTE CONSISTING FROM A PAIR OF BIPOLAR TRANSISTORS AND ACTIVE INDUCTANCE

The paper considers optoelectronic devices for temperature measurements that comprise a wide range of various units. High technical and operational characteristics of optic temperature sensors enable their application in different fields of economy, science and technology.

***Key words**: Optic-frequency temperature sensor, negative resistance, temperature pickup, voltage-frequency converter, temperature, capacitive resistance, active inductance.*

Introduction

The problem of creating a system of unified optic-frequency temperature sensors with high metrological characteristics and the initial signal that could be converted into a code form with inconsiderable errors remains quite an important one. Application of the reactive properties of transistor structures for voltage-frequency conversion is one of the most efficient ways to solve this problem.

This work is devoted to the problem of creation and investigation of optic-frequency temperature sensors the operation of which is based on the functional relationship between the impedance of semiconductor devices and the temperature – one of the most common non-electric quantities. This problem is of theoretical and practical interest and, therefore, can be considered actual.

Main part

The device shown in fig. 1 enables efficient solution of the remote temperature measurement problem. The operation principle of the optic-frequency temperature sensor is based on the action of temperature variations received by the temperature pickup IRA – E420S1 produced by Murata (photoelectric infrared pickup). In this way the pickup output voltage is changed, which results in changes of capacitance component of the total resistance at the collector-collector electrodes of the pair of bipolar transistors. This causes changes of the oscillatory circuit resonant frequency.

Until the temperature remains unchanged, no measurements are performed. At the moment when negative inductance appears at the collector-collector electrodes of the pair of bipolar transistors, electric oscillations are observed in the circuit. The circuit is formed by parallel connection of the total capacitive resistance at the collector-collector electrodes of the pair of bipolar transistors VT2, VT3, passive inductance L and active inductance formed by connecting condenser C1, transistor VT4, resistor R6. During the next temperature change that is received by the pickup its initial voltage is changed, which results in changes of the capacitive component of the total resistance at the collector-collector electrodes of the pair of bipolar transistors. This causes changes in resonant frequency of the oscillatory circuit.

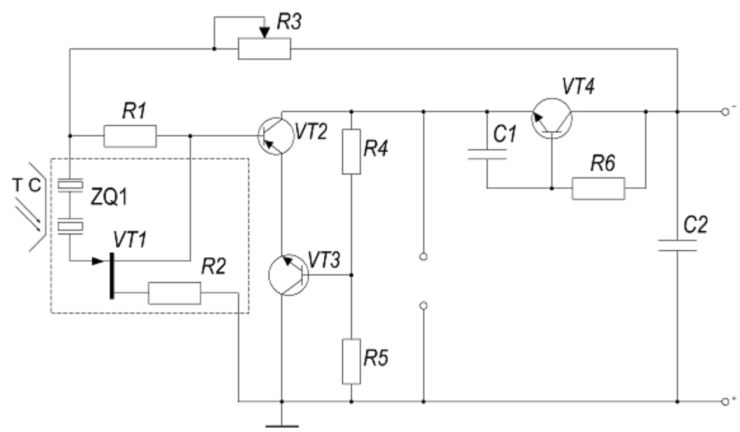

Fig. 1. Electric circuit of the optic-frequency temperature sensor on the basis of a structure consisting from a pair of bipolar transisitors and active inductance

There exists a necessity to prove theoretically and practically that at collector-collector electrodes of bipolar transistors negative resistance is observed that corresponds to the falling section of volt-ampere (VAC) characteristic. Besides, in order to study optic-frequency temperature sensor operation in dynamic conditions it is necessary to obtain the relationship of the active and reactive component of the complex resistance at the electrodes of the collector-collector structure. To achieve this, we designed a circuit of the device where equivalent transistor circuits are taken into account. The obtained circuit is shown in fig. 2.

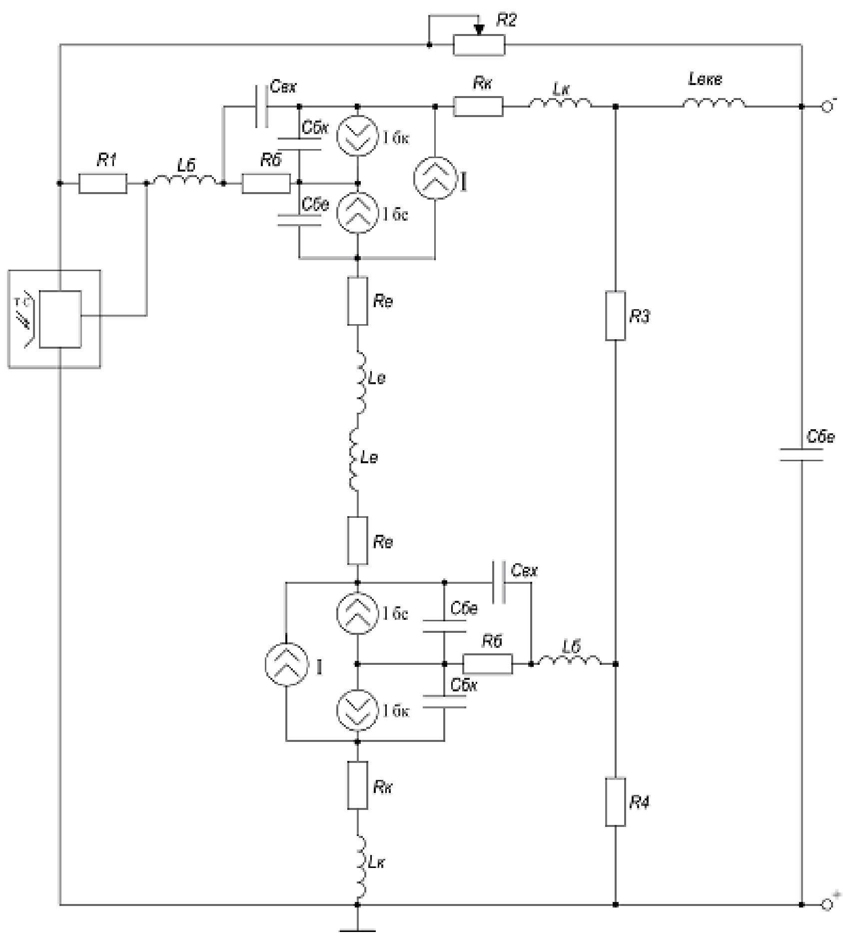

Fig. 2. Equivalent circuit of the optic-frequency temperature sensor

For the convenience of calculations we used a simplified equivalent circuit of the optic-frequency temperature sensor, presented in fig.3, where $Z_{R2} = R_2; Z_{R3} = R_3; Z_{R4} = R_4;$ $Z_{RБ} = R_B; Z_{LБ} = j\omega L_B;$

$$Z_{CBX} = \frac{-j}{\omega C_{BX}};\ Z_{LEKB} = j\omega L_{EKB}; Z_{RLK} = R_C + j\omega L_C;\ Z_{CБК} = \frac{-j}{\omega C_{BC}}; Z_{CБЕ} = \frac{-j}{\omega C_{BE}};$$

$$Z_{RLE} = R_E + j\omega L_E.$$

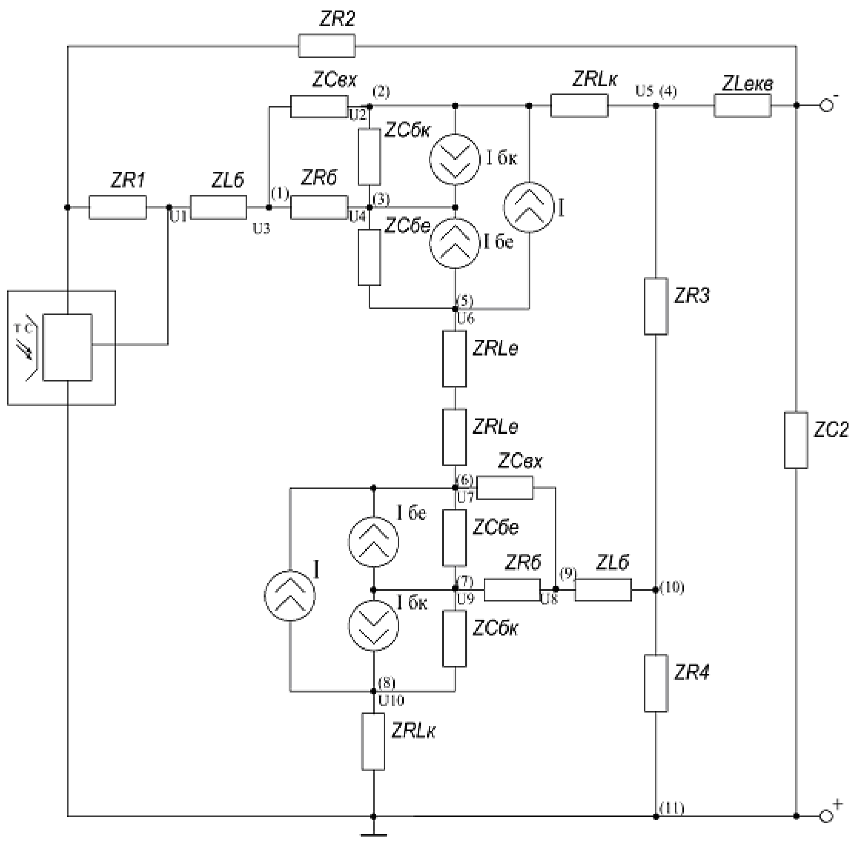

Fig. 3. A simplified equivalent circuit of the optic-frequency temperature sensor

Let us perform calculations of the given model by solving the system of equations.

The obtained system of equations is solved using the matrix technique. For this we shall write the expression of the main system matrix – A, the column of free terms – B and find the columns of the system solution – X accordingly.

$$A=\begin{pmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{22} & 0 & 0 & a_{25} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{45} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{54} & 0 & a_{56} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{66} & a_{67} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{77} & a_{78} & a_{79} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{89} & a_{810} \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{97} & a_{98} & 0 & 0 \\ a_{101} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{110} \end{pmatrix},$$

$$B=\begin{pmatrix} 0 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \\ b_8 \\ b_9 \\ b_{10} \end{pmatrix},$$

where $a_{11}=\dfrac{1}{Z_{R2}+Z_{LБ}}$; $a_{12}=\dfrac{1}{Z_{СВХ}}$; $a_{13}=-\dfrac{1}{Z_{RБ}}$; $a_{22}=-\dfrac{1}{Z_{СВХ}}-\dfrac{1}{Z_{СБК}}$; $a_{25}=\dfrac{1}{Z_{RLK}}$; $a_{32}=\dfrac{1}{Z_{СБК}}$; $a_{33}=\dfrac{1}{Z_{RБ}}$; $a_{34}=-\dfrac{1}{Z_{СБЕ}}$; $a_{45}=\dfrac{1}{Z_{RLK}}$; $a_{54}=\dfrac{1}{Z_{СБЕ}}$; $a_{56}=-\dfrac{1}{2Z_{RLБ}}$; $a_{66}=\dfrac{1}{2Z_{RLE}}$; $a_{67}=-\dfrac{1}{Z_{СВХ}}-\dfrac{1}{Z_{СБЕ}}$; $a_{77}=\dfrac{1}{Z_{СБЕ}}$; $a_{78}=\dfrac{1}{Z_{RБ}}$; $a_{79}=-\dfrac{1}{Z_{СВК}}$; $a_{89}=\dfrac{1}{Z_{СВК}}$; $a_{810}=-\dfrac{1}{Z_{RLK}}$; $a_{97}=\dfrac{1}{Z_{СВХ}}$; $a_{98}=-\dfrac{1}{Z_{RБ}}$; $a_{1010}=\dfrac{1}{Z_{RLK}}$; $b_2=I-I_{BC}$; $b_3=I_{BC}+I_{BE}$; $b_4=-\dfrac{U_S}{Z_C+Z_{LEKB}}-+\dfrac{U_S}{Z_{R3}}$; $b_5=-I_{BE}-I$; $b_6=I+I_{BE}$; $b_7=-I_{BC}-I_{BE}$; $b_8=I_{BC}-I$; $b_9=-\dfrac{U_S}{Z_{R3}}+\dfrac{U_S}{Z_{R4}+Z_{R3}}$; $b_{10}=-\dfrac{U_S}{Z_{R4}+Z_{R3}}+\dfrac{U_S}{Z_C}$.

The inductance value of the active element is described by the expression:

$$L_{EKB}=\frac{1}{\omega}\cdot\frac{A_4A_1+A_3A_2}{A_1^2+A_2^2}, \tag{1}$$

$$\text{where } A_1 = \omega C_1 \cdot \left[\left(\mathrm{R_B} + \mathrm{R_E} - \mathrm{R}_6\alpha_1\right)^2 - \left(\mathrm{R}_6\alpha_2\right)^2 + \frac{1}{(\omega C_1)^2} \right],$$

$$A_2 = \omega C_1 \cdot \left[2\mathrm{R}_6\alpha_2\left(\mathrm{R_B} + \mathrm{R_E} - \mathrm{R}_6\alpha_1\right)\right],$$

$$A_3 = \left[\mathrm{R}_6\alpha_1\left(\mathrm{R_B} + \mathrm{R_E} - \mathrm{R}_6\right) - \left(\mathrm{r_B} + \mathrm{r_E}\right)\frac{\mathrm{R}_6{}^2}{\mathrm{R_C}} - \frac{2\alpha_1\mathrm{R}_6{}^3}{\mathrm{R_C}} + \frac{\alpha_2\mathrm{R}_6{}^2}{(\omega C_1)^2} \right],$$

$$A_4 = \left[2\mathrm{R}_6{}^2\alpha_1\alpha_2 - \left(\mathrm{R_B} + \mathrm{R_E}\right)\mathrm{R}_6\alpha_2 + \frac{2\alpha_2\mathrm{R}_6{}^3}{\mathrm{R_C}} \right],$$

$\alpha_1 = \dfrac{\alpha_0}{1+(f/f_\alpha)^2}$ - real component of the coefficient of current transfer in the circuit with common base, $\alpha_2 = \dfrac{\alpha_0 f/f_\alpha}{1+(f/f_\alpha)^2}$ – imaginary component of the current transfer coefficient in the circuit with general base, $\mathrm{R_B}, \mathrm{R_E}, \mathrm{R_C}$ – resistances of the base, emitter and collector of VT4 transistor correspondingly, f_α – limiting frequency of the bipolar transistor in the circuit with common base, f – operating frequency, $\omega = 2\pi f$ – circular frequency.

Quality factor of the active inductive element is determined by the formula:

$$Q = \frac{(A_4 A_1 + A_3 A_2)\omega C_1}{\omega C_1 (A_3 A_1 + A_4 A_2) - (A_1^2 + A_2^2)}, \tag{2}$$

Currents of the base-emitter I_{BE} and base-collector I_{BC} are described by the expressions:

$$I = \frac{I_{BE} - I_{BC}}{Q}, \tag{3}$$

$$I_{BE} = I_S \exp\left(\frac{U_{BE}}{NE \cdot V_t} - 1 \right), \tag{4}$$

$$I_{BC} = I_S \exp\left(\frac{U_{BC}}{NC \cdot V_t} - 1 \right), \tag{5}$$

$$I_S = I_{SS} \exp\left(\frac{U_{jS}}{NS \cdot V_t} - 1 \right), \tag{6}$$

where Q – charge in the base; $V_t = kT/q$; I_{SS} – inverse current of p-n transition of the substrate; U_{BE} – base-emitter voltage; U_{BC} – base-collector voltage; U_{jS} – contact potential difference of the collector-substrate transition; NE - imperfection coefficient of the emitter transition; NC – imperfection coefficient of the collector transition; NS – imperfection coefficient of the substrate transition.

After solving the obtained equation set, the expression for the total resistance of the optic-frequency temperature sensor is found:

$$Z=\frac{U_S}{\dfrac{Z_{R2}+Z_{RLE}}{Z_{LБ}-Z_{RLE}}\cdot\left[U_{:S}\left(\dfrac{1}{Z_C}+\dfrac{1}{Z_{R3}}\right)-2I_{BE}-I+I_{\mathbf{BC}}-\dfrac{Z_{СБК}+Z_{СВХ}}{Z_{СБК}\cdot Z_{СВХ}}\left(U_Ж\left(\dfrac{1}{Z_C+Z_{LEKB}}-\dfrac{1}{Z_{R3}}\right)-I-I_{BC}\right)\right]}. \quad (7)$$

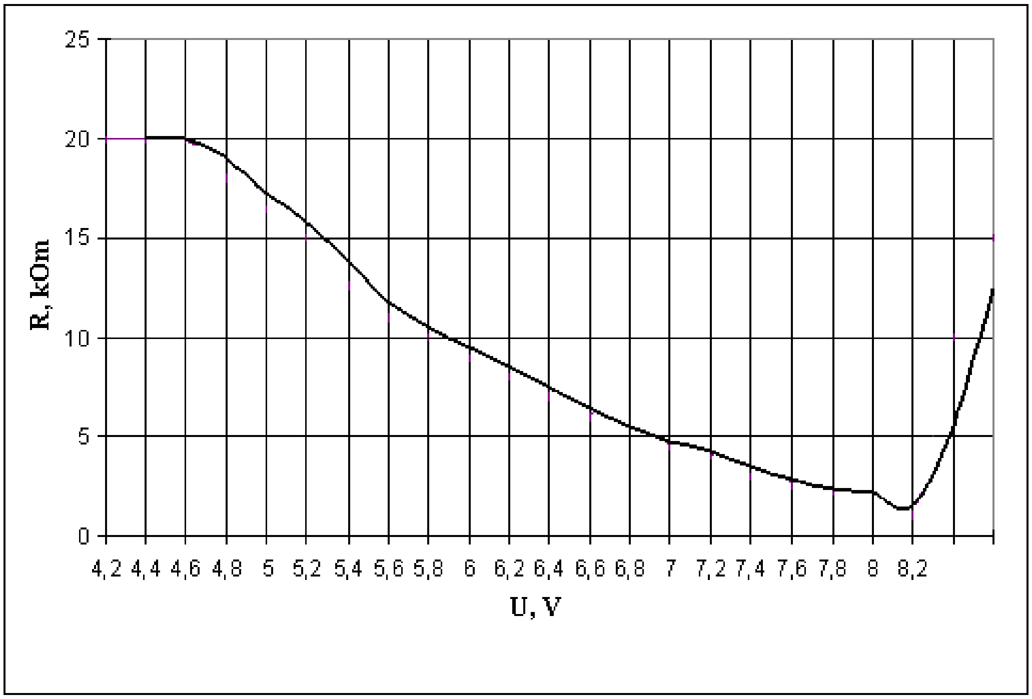

Fig. 4. Theoretical dependence of the active component of the total complex resistance on the supply voltage for optic-frequency temperature sensor based on the structure consisting from a pair of bipolar transistors and active inductance

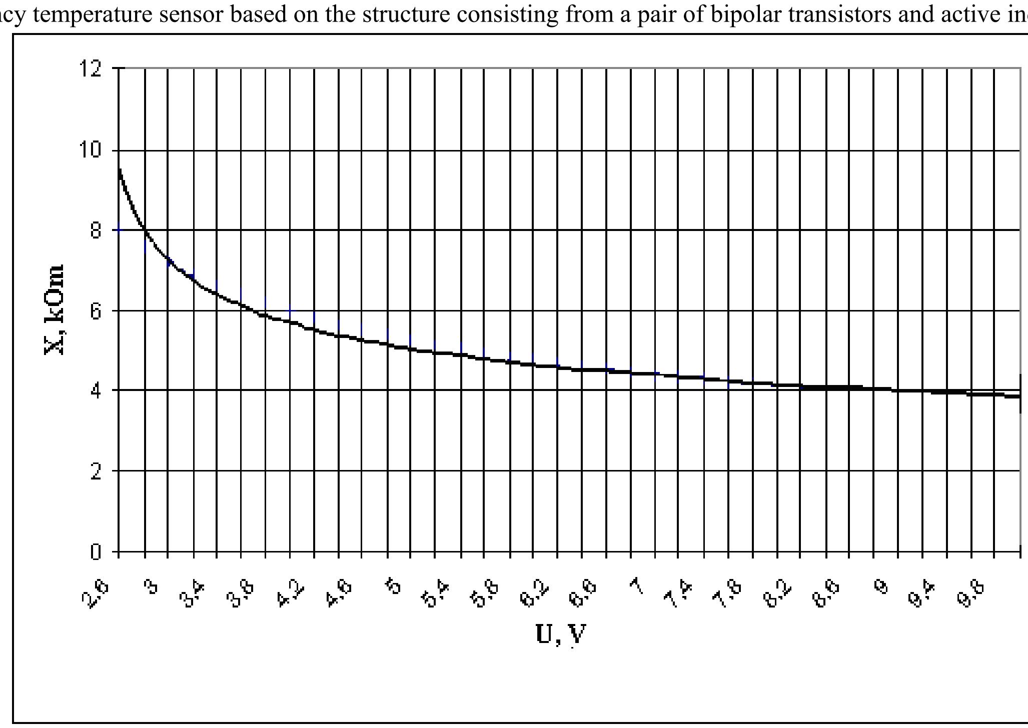

Fig. 5. Theoretical dependence of the reactive component of the total complex resistance on the supply voltage for optic-frequency temperature sensor based on the structure consisting from a pair of bipolar transistors and active inductance

Conclusions

1. For the first time mathematical models of the optic-frequency temperature sensors were constructed on the basis of structure consisting from a pair of bipolar transistors and active inductance.

2. Equivalent circuits of the devices are presented taking into account equivalent transistor circuits. As a result, an equivalent and simplified equivalent circuits of the optic-frequency temprature sensor were obtained.

3. By the development and solution of the equation system calculation of the mathematical models of the optic-frequency temperature sensor, based on the structure consisting from a pair of bipolar transistors and active inductance, was performed.

4. After solving the obtained equation system, an expression was found for the total resistance of the optic-frequency temperature sensor based on the structure consisting from a pair of bipolar transistors and active inductance.

5. Theoretical dependences of the reactive and active components of the total complex resistance on the supply voltage were obtained.

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