http://doi.org/10.35784/iapgos.3476

received: 2.02.2023 | revised: 12.03.2023 | accepted: 13.03.2023 | available online: 31.03.2023

SELF-OSCILLATING PARAMETRIC HUMIDITY SENSOR WITH FREQUENCY OUTPUT SIGNAL

Iaroslav O. Osadchuk, Oleksandr V. Osadchuk, Vladimir S. Osadchuk, Lyudmila V. Krylik

Vinnytsia National Technical University, Vinnytsia, Ukraine

Abstract. *A self-oscillating parametric humidity sensor has been developed that implements the principle of "humidity-frequency" conversion into hybrid integrated circuit based on a microelectronic transistor structure with a negative differential resistance, in which the humidity-sensitive element is a resistor of the HR202 type. For the purposes of determining parameters self-oscillating parametric humidity sensor with frequency output a mathematical model has been developed that takes into account the effect of humidity on a sensitive resistive element, which is an integral element of the device. Based on the mathematical model, analytical expressions for the transformation function and the sensitivity equation are obtained. It is shown that the main contribution to the conversion function is made by relative humidity. The computer simulation and experimental studies of a self-oscillating parametric humidity sensor with a frequency output signal contributed to obtaining the main parameters and characteristics, such as the dependence of the generation frequency on changes in relative humidity in the range from 30% to 99%, the change in sensitivity on relative humidity, the dependence of the active and reactive components of the impedance in the frequency range from 50 kHz to 2 GHz; standing wave ratio, change in logarithmic magnitude and spectra of the output signal of a parametric humidity sensor with a frequency output signal in the LTE-800 Downlink frequency range. The obtained electrical characteristics confirm the operability of the developed device. The sensitivity of the developed self-oscillating parametric humidity sensor in the range of relative humidity change from 30% to 99% has a value from 332.8 kHz/% to 130.2 kHz/%.*

Keywords: self-oscillating parametric humidity sensor with frequency output, negative differential resistance, humidity-sensitive resistor

SAMOOSCYLACYJNY PARAMETRYCZNY CZUJNIK WILGOTNOŚCI Z CZĘSTOTLIWOŚCIOWYM SYGNAŁEM WYJŚCIOWYM

Abstrakcyjny. *Opracowano samooscylujący parametryczny czujnik wilgotności realizujący zasadę konwersji „wilgotność-częstotliwość" do hybrydowego układu scalonego opartego na mikroelektronicznej strukturze tranzystorowej o ujemnej rezystancji różnicowej, w której elementem czułym na wilgotność jest rezystor typu HR202 typ. Na potrzeby wyznaczania parametrów samooscylującego parametrycznego czujnika wilgotności z wyjściem częstotliwościowym opracowano model matematyczny uwzględniający wpływ wilgoci na czuły element rezystancyjny, będący integralną częścią urządzenia. Na podstawie modelu matematycznego uzyskuje się wyrażenia analityczne dla funkcji transformacji i równania wrażliwości. Pokazano, że główny udział w funkcji konwersji ma wilgotność względna. Symulacja komputerowa i badania eksperymentalne samooscylującego parametrycznego czujnika wilgotności z wyjściowym sygnałem częstotliwościowym przyczyniły się do uzyskania głównych parametrów i charakterystyk, takich jak zależność częstotliwości generacji od zmian wilgotności względnej w zakresie od 30% do 99%, zmiana czułości na wilgotność względną, zależność składowej czynnej i reaktywnej impedancji w zakresie częstotliwości od 50 kHz do 2 GHz; współczynnika fali stojącej, zmiany wielkości logarytmicznej i widma sygnału wyjściowego parametrycznego czujnika wilgotności przy częstotliwościowym sygnale wyjściowym w zakresie częstotliwości LTE-800 Downlink. Uzyskane charakterystyki elektryczne potwierdzają sprawność opracowanego urządzenia. Czułość opracowanego samooscylującego parametrycznego czujnika wilgotności w zakresie zmian wilgotności względnej od 30% do 99% przyjmuje wartość od 332,8 kHz/% do 130,2 kHz/%.*

Słowa kluczowe: samooscylacyjny parametryczny czujnik wilgotności z wyjściem częstotliwościowym, ujemna rezystancja różnicowa, rezystor wrażliwy na wilgoć

Introduction

The creation and maintenance of optimal microclimate parameters in industrial premises is primarily determined by the sanitary, hygienic and technological requirements of production, since the deviation of microclimate parameters from the norms leads to disruptions in the flow of technological processes in the national economy and affects the well-being of producers (people). The effectiveness of technical diagnostic tools and devices for monitoring environmental parameters depends on the quality of primary transducers, which are the main sensitive organs of measuring equipment. Humidity sensors are an important type of sensors for physical quantities [3–5, 10, 11, 14].

Currently, there is a rapid development of semiconductor humidity sensors, the creation of which became possible only at a certain stage in the development of science, as well as microelectronics technology. The use of modern microelectronic technologies contributes to the development and manufacture of microelectronic humidity sensors with high accuracy and sensitivity to the measuring parameter and insensitive to other external factors, small weight and size, and low power consumption [1, 8, 12, 13]. It should be noted that the existing analog measuring transducers have a number of disadvantages, which include a small output signal, significant measurement errors, as well as low sensor output signal powers, which leads to low noise immunity and low speed [15–19].

1. Analysis of recent research and publications

A promising direction in the development and creation of microelectronic humidity sensors is research in the field of humidity frequency transducers based on transistor structures with negative differential resistance. Studies in this area have shown that reactive properties and negative differential resistance are inextricably linked, and the versatility and simplicity of radio electronic devices based on transistor structures with negative resistance is the prospect of their practical use. Self-oscillating parametric humidity sensors that implement the "humidity-frequency" conversion principle are characterized by simplicity and versatility, as well as accuracy and noise immunity [6, 7, 22].

2. Formulation of the problem

The aim of the work is to create and study a self-oscillating parametric humidity sensor based on a microelectronic transistor structure, in which the bipolar and field-effect transistors act as active elements of the self-oscillator. In this oscillator, energy losses in the oscillatory system are compensated by the energy of negative differential resistance, and a humidity-sensitive resistive element is included in the feedback circuit.

To achieve the goals in the article, you need to solve the following tasks:

1. analyze the existing scientific sources, as well as justify the use of a semiconductor transistor structure with a negative differential resistance to build self-oscillating parametric humidity sensors;

2. to develop a mathematical model of a parametric humidity sensor, which takes into account the dependence of the parameters of bipolar and field-effect transistors on power supply modes and changes in humidity acting on a humidity-sensitive resistive element and its effect on the output frequency of a self-oscillating parametric sensor;
3. to obtain the parametric dependence of the transformation functions and the sensitivity of the self-oscillating sensor on changes in humidity;
4. to carry out experimental studies of a self-oscillating parametric humidity sensor;
5. draw conclusions on the conducted research.

3. Mathematical model of self-generating humidity sensor

The self-oscillating humidity sensor with a frequency output signal is built on the basis of a microelectronic transistor structure with a negative differential resistance, in which the humidity-sensitive element is a resistor of the HR202 type (Fig. 1) [23].

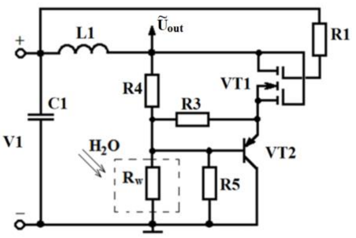

Fig. 1. Electric circuit of self-oscillating humidity sensor with frequency output signal

The self-oscillating humidity sensor with a frequency output signal consists of a field effect transistor VT1 and the bipolar transistor VT2, a humidity-sensitive resistor R_W, resistances R1, R3, R4, R5, capacitance C1 and inductance L1. The oscillatory circuit of the self-oscillating sensor is formed by the equivalent impedance capacitance at the drain electrodes of the field-effect transistor VT1 and the collector of the bipolar transistor VT2, as well as the passive inductance L1.

The humidity-sensitive element is included in a resistive divider R4-R5 with parallel connection to the resistor R5, which operates on direct current and provides a choice of operating point for the bipolar transistor VT2. A change in the resistance of the humidity-sensitive resistive element with a change in moisture causes a shift in the operating point of the bipolar transistor VT2, which in turn causes a change in the operating point on the volt-ampere characteristics of the self-oscillating parametric transducer, which is preselected in the falling section. Due to the fact that through a humidity-sensitive resistor at a supply voltage of 5 V and maximum humidity, when its resistance drops to several kilo Ohms, it is necessary to limit the flowing current to about 1.5 mA, resistor R5 was connected in parallel. With such a circuit solution, the direct current flowing through the humidity-sensitive element does not exceed 1.2 mA and the maximum voltage drop is 1.45 V, which does not allow it to fail.

The humidity-sensitive resistor R_W is affected by a change in humidity, which leads to a change in both the equivalent capacitance of the oscillatory circuit and the negative differential resistance at the output of the humidity sensor, which causes a change in the resonant frequency of the self-oscillating parametric sensor. Energy losses in the oscillatory circuit are compensated by the energy of the negative differential resistance [18]. Resistors R1, R3, R4, R5 supply power to the self-oscillating parametric sensor through a constant voltage source V1. Capacitance C1 prevents the passage of high-frequency alternating current through the DC voltage source. The current-voltage characteristic of the self-oscillating parametric humidity sensor has a descending section, confirming the existence of a negative differential resistance in this section. The circuit of a self-oscillating parametric humidity sensor with a humidity-sensitive resistive element HR202 (Fig. 1) was assembled on a BFT93 bipolar transistor and a BF998 field-effect transistor to ensure operation in the microwave range. The mode of transistors VT1 and VT2 for direct current was as follows: the current in the drain circuit of the field-effect transistor VT1 is 2.25 mA, and the drain voltage is 5 V. The circuit resistances have the following values R1 = 1.0 kOhm; R3 = 5.0 kOhm; R4 = 5.2 kOhm; R5 = 20.0 kOhm. The oscillator inductance has a value of 1.7 nH. Based on the experimental studies, the above operation mode, at a humidity of 30%, corresponded to the generation frequency of 822.0 MHz, and at 99% humidity – 806.8 MHz. The proposed generator circuit makes it possible to obtain an output voltage of up to 4.7 V in a wide frequency range. The frequency instability of the self-oscillating parametric humidity sensor corresponded to the level of $1.35 \cdot 10^{-5}$ Hz.

To determine the conversion function and the sensitivity equation, an equivalent high-frequency nonlinear circuit of a self-oscillating humidity sensor with a frequency output signal with a humidity-sensitive resistive element was developed (Fig. 2).

Due to the fact that the humidity-sensitive resistor operates on direct current in the non-linear equivalent circuit of the self-oscillating transducer, its inductive properties are not taken into account, since they are not distributed. Due to the comb structure of the humidity-sensitive resistor, in the equivalent circuit, its capacitive properties can be taken into account by connecting the capacitance in parallel, but the change in this capacitance due to changes in humidity in this sensor design is a fraction of a picofarad.

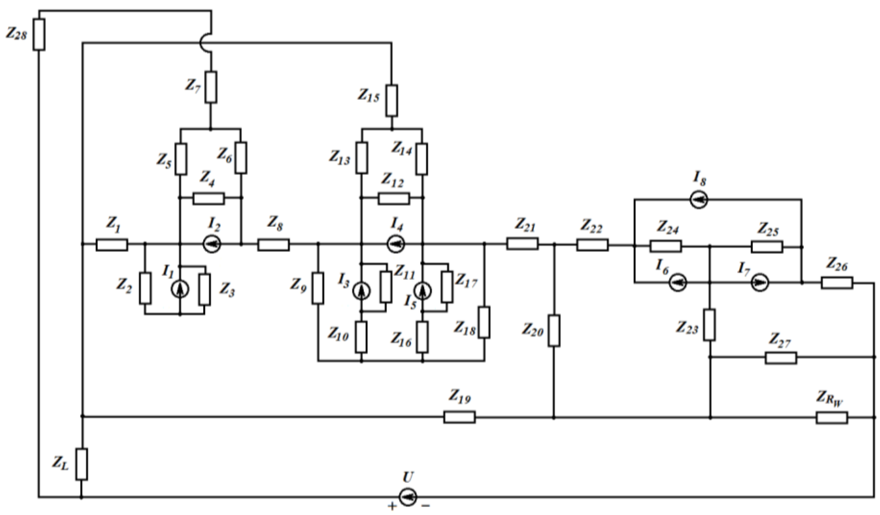

Fig. 2. Transformed equivalent high-frequency nonlinear circuit self-oscillating humidity sensor

The elements of the equivalent high-frequency nonlinear circuit (Fig. 2) are described by the following quantities:

$$Z_L = j\omega L,\ Z_{R_W} = \frac{R_W(W)}{1+\omega^2 R_W^2(W) C_W^2} - j\frac{R_W^2(W)\omega C_W}{1+\omega^2 R_W^2(W) C_W^2},$$

$$Z_1 = R_{d1} + R'_{d1} + j\omega L_{d1},\ Z_2 = R_{bd1} - j\frac{1}{\omega C_{bd1}},\ Z_3 = \frac{1}{j\omega C_d},$$

$$Z_4 = R_{ds1},\ Z_5 = \frac{1}{j\omega C_{gd1}},\ Z_6 = \frac{1}{j\omega C_{gs1}},$$

$$Z_7 = R_{g1} + R'_{g1} + j\omega L_{g1},\ Z_8 = R_{ds1},\ Z_9 = \frac{1}{j\omega C_{bd2}},$$

$$Z_{10} = R_{bd2},\ Z_{11} = \frac{1}{j\omega C'_d},\ Z_{12} = R_{ds2},\ Z_{13} = \frac{1}{j\omega C_{gd2}},$$

$$Z_{14} = \frac{1}{j\omega C_{gs2}},\ Z_{15} = R_{g2} + R'_{g2} + j\omega L_{g2}, Z_{16} = R_{bs3},$$

$$Z_{17} = \frac{1}{j\omega C_s},\ Z_{18} = \frac{R_{b2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2} - j\frac{R_{b2}^2 \omega C_{bs2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2},$$

$$Z_{19} = R_4,\ Z_{20} = R_3,\ Z_{21} = R_{s2} + R'_{s2} + j\omega L_{s2},$$

$$Z_{22} = R_e + R'_e + j\omega L_e,\ Z_{23} = R_B + R'_B + j\omega L_B,\ Z_{24} = \frac{1}{j\omega C_e},$$

$$Z_{25} = \frac{1}{j\omega C_c},\ Z_{26} = R_c + R'_c + j\omega L_c,\ Z_{27} = R_5,\ Z_{28} = R_1$$

where W – humidity; L – inductance of the oscillatory circuit; $R_W(W)$ – resistance of the humidity-sensitive resistive element; R_1 – resistance serves to prevent breakdown of the gate dielectric; R_3, R_4 – divider resistance; R_5 – resistance is used to linearize the characteristics of the humidity sensitive resistive element; R_d – drain resistance; R'_d – ohmic drain resistance; L_d – drain electrode inductance; C_{bd} – substrate-drain capacity; R_b – resistance of the substrate; C_{bs} – substrate-source capacitance; R_{bd1}, R_{bd2} – volume resistance p-n substrate-drain junction; R_{bs3} – volume resistance p-n substrate-source junction; C_d, C'_d – drain junction capacitance p-n; C_s – capacitance p-n source junction; R_{ds} – drain-source resistance; C_{gs} – gate-source capacitance; C_{gd} – gate-drain capacity; R_g – resistance of the gate electrode; R'_g – ohmic resistance of the gate electrode; L_g – inductance of the gate electrode; I_1 – substrate-drain junction current; I_2, I_4 – source-drain currents; I_3 – substrate-drain-source junction current; I_5 – substrate-source transition current; R_{ds1} – total resistance of the drain-source of the first gate of the double-gate transistor VT1; R_s – source resistance; R'_s – ohmic source resistance; L_s – source electrode inductance; R_B – base resistance; R'_B – ohmic resistance of the base electrode; L_B – base electrode inductance; C_e – capacitance of the emitter junction; C_c – capacitance of the collector junction; R_e – resistance of the emitter junction; R'_e – ohmic resistance of the emitter electrode; L_e – emitter electrode inductance; R_c – resistance to the collector junction; R'_c – ohmic resistance of the collector electrode; L_c – collector electrode inductance; I_6 – emitter-base current of the transistor VT2; I_7 – collector-base current of the transistor VT2; I_8 – emitter-collector current of the transistor VT2 [9, 21, 25].

Without knowing the parameters of humidity transducers, it is impossible to create them, so the task was to develop a mathematical model, based on the solution of which the conversion function and sensitivity equations, the main metrological parameters of measuring transducers will be determined. For this, a high-frequency nonlinear circuit of a self-oscillating humidity sensor with a frequency output signal with a humidity-sensitive resistive element HR202 was developed (Fig. 2).

According to the positive feedback loop of this circuit, an equation is defined, on the basis of which an analytical expression of the conversion function is obtained, that is, the dependence of the output frequency on the change in humidity (F_0):

$$F_0 = \frac{\pi \cdot R_W(W) \cdot C_{eb} \cdot C_{ds} \cdot C_{cb}}{4\cdot\pi^2 \cdot L \cdot R_W(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}} \pm \pm\frac{\sqrt{\pi^2 \cdot R_W^2(W)\cdot C_{eb}^2 \cdot C_{ds}^2 \cdot C_{cb}^2 + A_6}}{4\cdot\pi^2 \cdot L \cdot R_W(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}} \tag{1}$$

where

$$A_1 = 4\cdot\pi^2 \cdot L\cdot R_W^2(W)\cdot C_{eb}\cdot C_{ds}^2 \cdot C_{cb}^2,$$

$$A_2 = 4\cdot\pi^2 \cdot L^2 \cdot C_{eb}^2 \cdot C_{ds}^2,$$

$$A_3 = 4\cdot\pi^2 \cdot L\cdot R_W^2(W)\cdot C_{eb}^2\cdot C_{ds} \cdot C_{cb}^2,$$

$$A_4 = L\cdot C_{eb}\cdot C_{ds}^2 + L\cdot C_{eb}^2 \cdot C_{ds},$$

$$A_5 = 4\cdot\pi^2 \cdot L\cdot R_W^2(W)\cdot C_{eb}^2\cdot C_{ds}^2 \cdot C_{cb},$$

$$A_6 = A_1 - A_2 + A_3 + A_4 + A_5.$$

Due to the fact that the humidity-sensitive resistor is included in the lower arm of the resistive divider, therefore, in the analytical equation of the conversion function, it is necessary to use the «-» sign and the output frequency of the transducer decreases with increasing humidity. If a humidity-sensing resistor is included in the upper arm of the resistive divider, the «+» sign must be used in the conversion function, and the output frequency of the transducer will increase with increasing humidity.

Based on equation (1), the analytical expression for the sensitivity (2) of the developed self-oscillating parametric humidity sensor is determined:

$$S_W^{F_0} = \frac{\pi\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}\left(\frac{\partial R_W(W)}{\partial W}\right)}{4\cdot\pi^2\cdot L\cdot R_W(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}} \pm \pm\frac{\frac{(B_1+B_2+B_3+B_4)\cdot\left(\frac{\partial R_W(W)}{\partial W}\right)}{\sqrt{\pi^2\cdot R_W^2(W)\cdot C_{eb}^2\cdot C_{ds}^2\cdot C_{cb}^2 + A_6}}}{4\cdot\pi^2\cdot L\cdot R_W(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}} - \left(\frac{\pi\cdot R_W(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}}{4\cdot\pi^2\cdot L\cdot R_W^2(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}} \pm \pm\frac{\sqrt{\pi^2\cdot R_W^2(W)\cdot C_{eb}^2\cdot C_{ds}^2\cdot C_{cb}^2 + A_6}\left(\frac{\partial R_W(W)}{\partial W}\right)}{4\cdot\pi^2\cdot L\cdot R_W^2(W)\cdot C_{eb}\cdot C_{ds}\cdot C_{cb}}\right) \tag{2}$$

where

$$B_1 = \pi^2 \cdot R_W(W)\cdot C_{eb}^2\cdot C_{ds}^2\cdot C_{cb}^2,$$

$$B_2 = 4\cdot\pi^2\cdot L\cdot R_W(W)\cdot C_{eb}\cdot C_{ds}^2\cdot C_{cb}^2,$$

$$B_3 = 4\cdot\pi^2\cdot L\cdot R_W(W)\cdot C_{eb}^2\cdot C_{ds}\cdot C_{cb}^2,$$

$$B_4 = 4\cdot\pi^2\cdot L\cdot R_W(W)\cdot C_{eb}^2\cdot C_{ds}^2\cdot C_{cb}.$$

The analytical dependence of the resistance $R_W(W)$ of the humidity-sensitive resistor on changes in humidity and temperature was obtained by approximating and interpolating this parameter provided by the manufacturer in the datasheet and described by expression (3). The error of the 3D mathematical description of the resistance $R_W(W)$ is 0.2%.

$$R_W(W,T) = a + b\ln(R_W) + c/T + d(\ln(R_W))^2 + e/T^2 + \\ + f(\ln(R_W))/T + g(\ln(R_W))^3 + h/T^3 + i(R_W)/T^3 + \\ + j(\ln(R_W))^2/T, \quad (3)$$

where T – ambient temperature; a,b,c,d,e,f,g,h,i,j – approximation coefficients:

a=160.6061051; b=–18.6534062; c=3789.316024; d=–1.04223052; e=–135316.566; f=531.6381046; g=0.103813382; h=733991.7173; i=2636.940718; j=–36.4837064.

On Fig. 3 shows a 3D model of the dependence of the resistance $R_W(W)$ of a humidity-sensitive resistor on changes in humidity and temperature. To reduce the error in the description of this parameter, it is necessary to calibrate and introduce a correction factor for each instance of the humidity-sensitive resistor, thus it is possible to increase the accuracy of measuring the informative parameter.

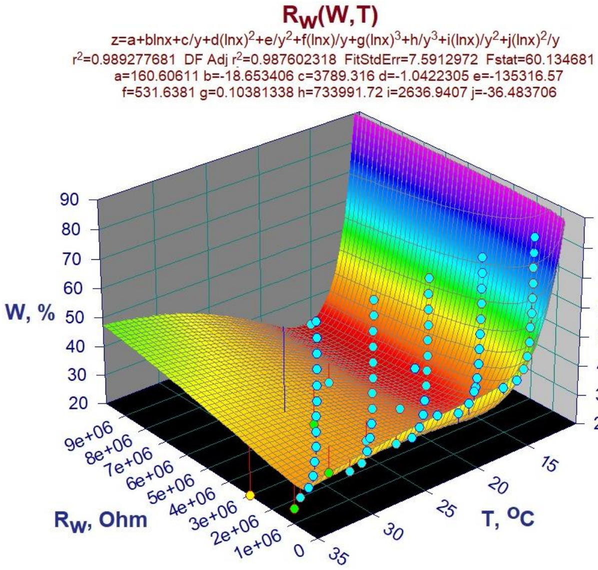

Fig. 3.3D model of the dependence of the resistance $R_W(W)$

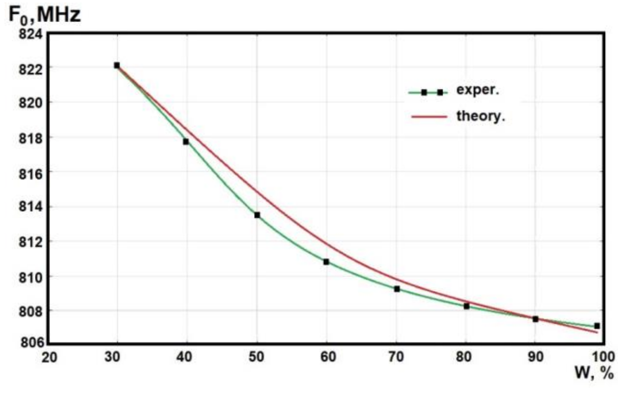

Fig. 4. Theoretical and experimental dependences generation frequency from changes in relative humidity and 25°C temperature

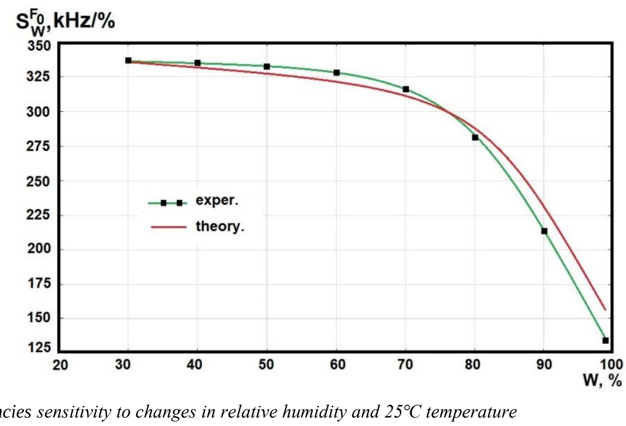

Fig. 5. Experimental and theoretical dependencies sensitivity to changes in relative humidity and 25°C temperature

On the basis of expression (1), the transformation function of a self-oscillating parametric humidity sensor was theoretically calculated and experimentally studied (Fig. 4).

Based on expressions (1) and (2) in the Scilab 6.11 environment, the conversion function and sensitivity of the self-oscillating parametric humidity sensor were calculated with parallel processing of experimental data, which are presented in Fig. 4 and Fig. 5.

The sensitivity of the developed self-oscillating parametric humidity sensor in the relative humidity range from 30% to 99% takes values from 332.8 kHz/% to 130.2 kHz/%. With the minimum sensitivity (130 kHz/%) and the standard method of measuring frequency, i.e. using a time gate of 1 sec., the frequency can be measured with an accuracy of 1 Hz, so 130000 readings fall on 1% humidity, and the entire range from 30% up to 99% - 10350000 counts, which corresponds to a 23-bit ADC. The measurement error of the developed self-oscillating parametric humidity sensor, according to this method, is 0.01%, despite the fact that a standard sensitive resistive element is used.

Since almost all semiconductor devices are subject, to a greater or lesser extent, to the influence of temperature changes, in the proposed self-oscillating parametric humidity sensor, it is necessary to take into account the effect of temperature on the output parameters of the device. One of the methods to compensate for the influence of temperature on the measuring transducer is the use of a microcontroller with an additional temperature sensor. Using the analytical expression (3) and subsequent mathematical processing of the informative signal, it is possible to compensate for the effects of temperature.

4. Computer modelling and experimental studies

To confirm the theoretical results and conduct experimental studies, the electrical circuit of a self-oscillating parametric humidity sensor with a humidity-sensitive resistive element (Fig. 1) was studied in the LTSpice XVII circuit simulation environment [24] (Fig. 6). The studies were carried out in the range of change in the resistance of the humidity-sensitive resistive element R2 from 1300 kOhm to 1.3 kOhm, which corresponds to an increase in the value of relative air humidity from 30% to 99% at a temperature of 25°C.

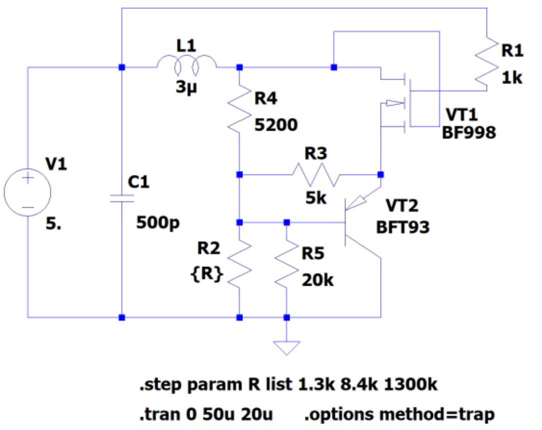

Fig. 6. Electric circuit of self-oscillating humidity sensor in a circuit environment LTSpice XVII simulation

On Fig. 7 shows the experimental dependence of the alternating voltage at the output of the self-oscillating sensor on time at a temperature of 25°C and a relative humidity of 30%, 75%, 99%.

Since the self-oscillating parametric humidity sensor is built on the basis of a transistor structure with a negative differential resistance and can operate in a wide frequency range, experimental studies were carried out from low frequencies to microwave frequencies to determine the optimal operating frequencies for various tasks of using the developed device. In the range from 50 kHz to 6 MHz to work directly with 8-bit microcontrollers, with some loss in measurement accuracy. From 50 kHz to 80 MHz for direct operation with 32-bit Teency-type microcontrollers with medium humidity measurement accuracy. From 50 kHz to 250 MHz for FPGA operation with high measurement accuracy and parallel data streams from multiple transducers. And finally, as the case considered in this paper, in the radio frequency range from hundreds of megahertz to 2 GHz, in the form of a radio frequency measuring transducer, with a high accuracy of measuring an informative parameter. Based on the above described applications of the self-oscillating parametric humidity sensor, experimental studies of the main parameters in the frequency range from 50 kHz to 2 GHz were carried out.

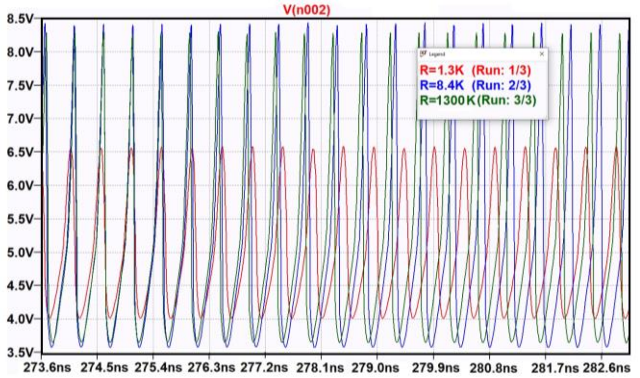

Fig. 7. Computer-simulated dependence of the alternating voltage at the output of a self-oscillating sensor in the LTSpice XVII circuit simulation environment

To conduct experimental studies of a self-oscillating sensor, an experimental setup has been developed, the block diagram of which is shown in Fig. 8.

The LiteVNA vector analyzer is an improvement over the popular NanoVNA and SAA2. It is currently one of the best vector handheld network analyzers (VNAs) and comprehensive indicators of semiconductor microwave devices, it is as small as the NanoVNA and is able to satisfy the ultra-wide measurement range from 50 kHz to 6.3 GHz [20]. To minimize power consumption and size, LiteVNA uses only one mixer with multiple internal RF switches for S11 and S21 measurements and IFFT calculations for TDR and DTF measurements. The LiteVNA vector analyzer provides faster scan speeds and more scan points, as well as a wider measurement range. Combined with an easy-to-use NanoVNA-compliant interface, LiteVNA can be easily used as a laboratory and field testing tool [20].

With a measurement range of up to 6.3 GHz, LiteVNA can handle common ham radio and IoT applications, as well as new 5 GHz tests to enable the latest 5.8 GHz Wi-Fi and 5.8 GHz imaging systems. Below are experimental data on the study of a self-oscillating humidity sensor with an output frequency signal. An experimental sample of a self-oscillating humidity sensor was developed on the basis of a double-gate MOSFET BF998 transistor and a bipolar transistor BFT93, forming a semiconductor structure with a negative differential resistance. In the Scilab 6.11 environment, on the basis of experimental data, the current-voltage characteristics of a transistor structure based on a BFT93 bipolar transistor and a BF998 MOSFET are constructed, which are shown in Fig. 9. The family of current-voltage characteristics of a transistor structure with a negative differential resistance was obtained by replacing the voltage divider R4, RW, R5 with an additional control voltage source V2. Experimental studies were carried out with control voltages in the range from 0.5 V to 3.0 V with a step of 0.5 V.

On Fig. 10 shows the Smith chart of the impedance S11, that is, the impedance of the structure under study in the frequency range from 50 kHz to 2 GHz. On Fig. 11 shows the impedance of the structure under study in polar coordinates. On Fig. 12 shows the standing wave ratio (SWR) in the same frequency range, and in Fig. 13 change in the active and reactive components of the self-oscillating humidity sensor impedance in the frequency range from 50 kHz to 2 GHz.

As noted above, the self-oscillating parametric humidity sensor is built on the basis of a transistor structure with a negative differential resistance, and a change in the impedance of the transistor structure makes a contribution to the frequency tuning from a change in humidity. Therefore, the study of the impedance (both active and reactive impedance components in a wide frequency range) of this structure is an integral part of the device development. This structure is a two-terminal, therefore, experimental studies of S11 parameters are carried out in the active mode with power supply through the RF + DC power module. It consists of high frequency inductors and capacitors with ultra-wide band, near ideal and no resonant point. An insulating capacitance is used to isolate DC current and prevent leakage of DC voltage into downstream circuits or instrumentation. The high frequency inductance isolates the AC information flow to prevent high frequency signals from leaking into the power system.

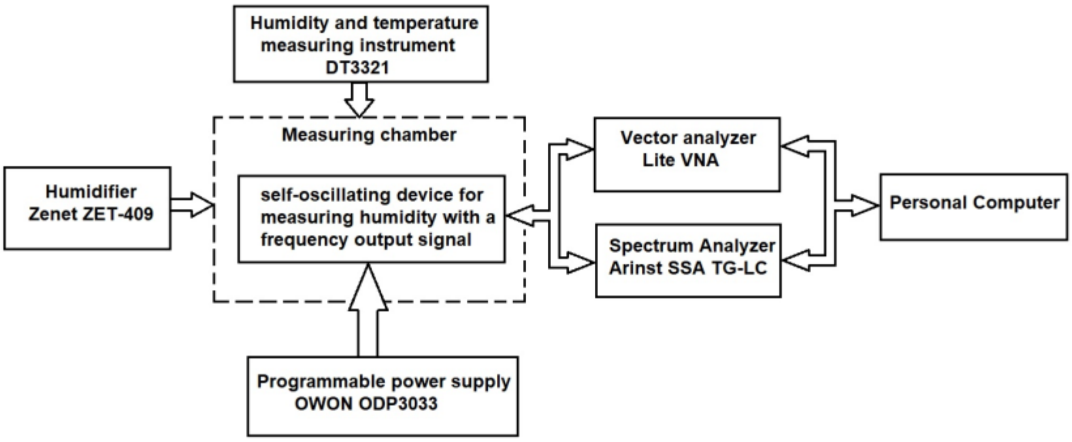

Fig. 8. Block diagram of the experimental setup

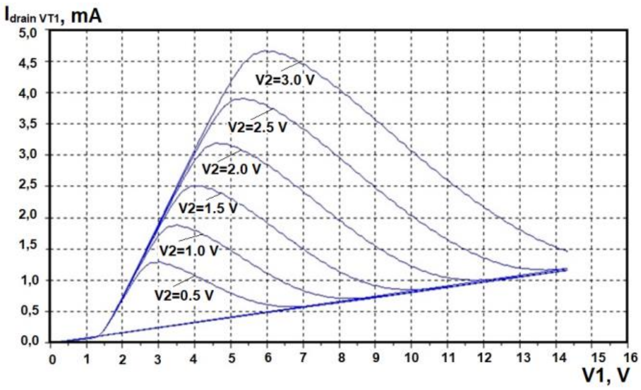

Fig. 9. Volt-ampere characteristics of the transistor structure based on bipolar BFT93 and MOSFET BF998 transistors

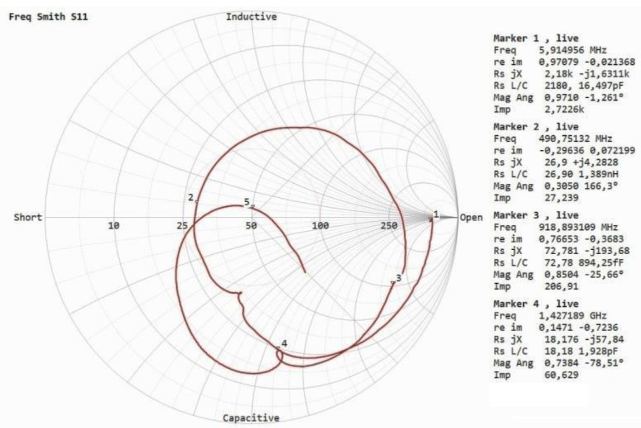

Fig. 10. Smith chart of the S11 self-oscillating impedance humidity sensor in the frequency range from 50 kHz to 2 GHz

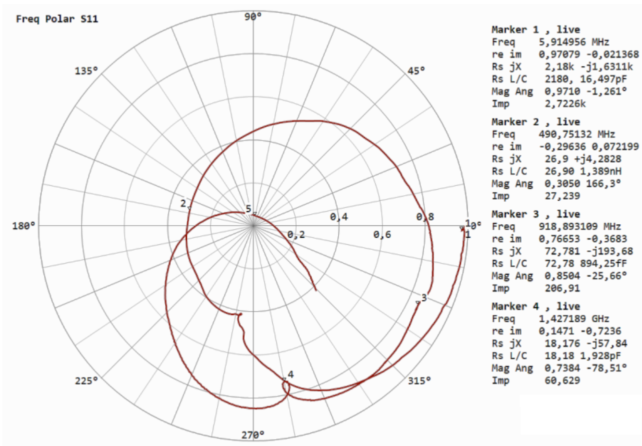

Fig. 11. Impedance S11 in polar coordinates of a self-oscillating humidity sensor in the frequency range from 50 kHz to 2 GHz

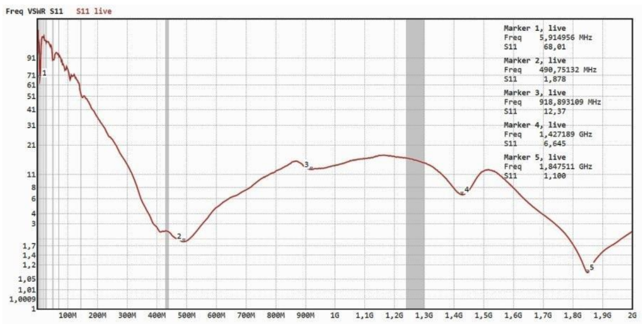

Fig. 12. SWR of self-oscillating humidity sensor in the frequency range from 50 kHz to 2 GHz

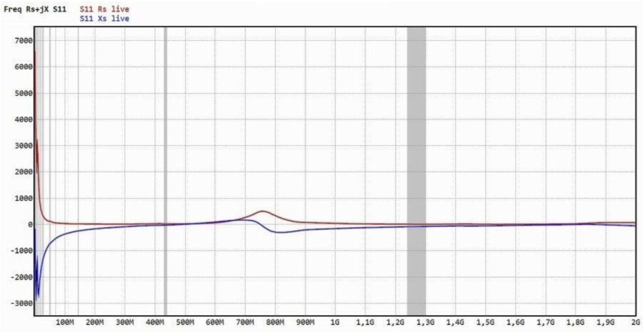

Fig. 13. Changing the active and reactive components of the impedance self-oscillating humidity sensor in the range frequencies from 50 kHz to 2 GHz

The experimental dependences of the real and imaginary parts of the parameter S11 are shown in Figs. 14, and in Fig. 15 shows the logarithmic magnitude of the self-oscillating sensor in the frequency range from 50 kHz to 2 GHz. The capacitance of the self-oscillating humidity sensor in the frequency range from 50 kHz to 150 MHz is shown in Fig. 16.

Experimental studies of the output signal spectra of the developed self-oscillating humidity sensor were carried out using an Arinst SSA TG-LC spectrum analyzer.

The LTE range for different countries and application systems is designed for frequencies from 450 MHz to 5925 MHz and is divided into 103 frequency bands. According to the customer's conditions, the frequency range of the humidity sensor is selected in the LTE-800 Downlink range. The 3GPP B20 (800 MHz) LTE band is the second most popular band used by public mobile operators to deploy LTE networks and is also well suited for wide regional coverage for in-building IoT coverage: NB-IoT (LTE Cat -NB1).The use of 800MHz spectrum helps operators to launch LTE services faster and meet market demands [2, 20].

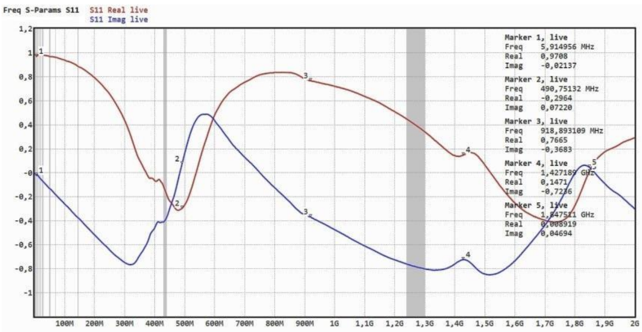

Fig. 14. Real and imaginary parts of the S11 self-oscillating sensor humidity in the frequency range from 50 kHz to 2 GHz

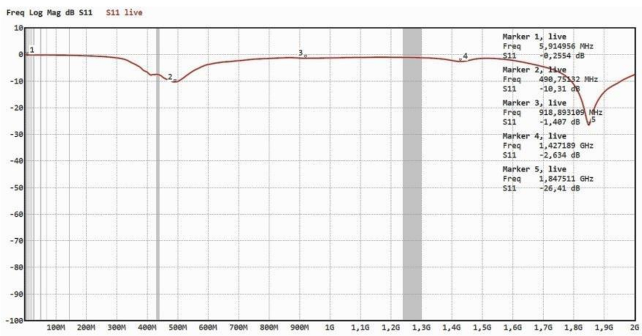

Fig. 15. Logarithmic magnitude of self-oscillating humidity sensor in the frequency range from 50 kHz to 2 GHz

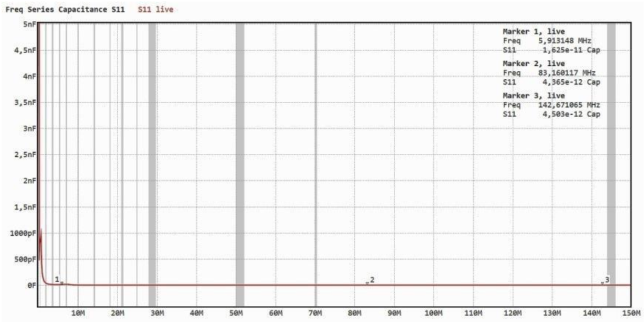

Fig. 16. Passing capacitance of self-oscillating humidity sensor in the frequency range from 50 kHz to 150 MHz

Self-oscillating parametric humidity sensor is designed in two versions. The first, as a radio transducer with its own data exchange protocol for a specialized measurement system, but in the LTE band, for deep protection of transmitted data. So is the second option, as a GFSK or MFSK modulation modulator, which is part of standard equipment with a generally accepted data transfer protocol.

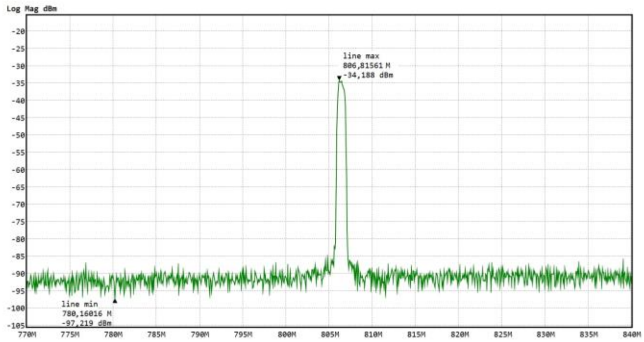

Fig. 17. Spectrum of a self-oscillating parametric humidity sensor with frequency output signal and humidity sensitive resistive element at 99% humidity and 25°C temperature

On Fig. 17 shows the spectrum of a self-oscillating parametric humidity sensor with a frequency output signal, designed based on a microelectronic transistor structure with a negative differential resistance, in which the moisture sensing element is a resistor, the transmission frequency is 806.8 MHz at a humidity of 99% and a temperature of 25°C.

Fig. 18 shows the spectrum of a self-oscillating parametric humidity sensor with frequency output at 30% humidity and 25°C, the transmission frequency has value 822.0 MHz.

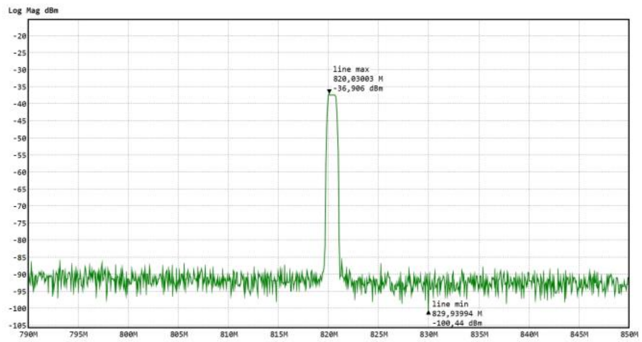

Fig. 18. Spectrum of self-oscillating parametric humidity sensor with frequency output signal at 30% humidity and 25°C temperature

5. Conclusions

1. A mathematical model has been developed for a self-oscillating parametric humidity sensor with a frequency output signal, which takes into account the influence of relative humidity on a sensitive resistive element, which is an integral element of a parametric transducer, which made it possible to obtain a conversion function, as well as a sensitivity function.
2. In the course of mathematical modeling, analytical expressions for the transformation function and the sensitivity equation of a self-oscillating parametric humidity sensor with an output frequency signal are obtained.
3. Computer modeling and experimental studies of a self-oscillating parametric humidity sensor were carried out, during which the main parameters and characteristics were obtained: the dependence of the generation frequency on changes in relative humidity in the range from 30% to 99%, the change in sensitivity on relative humidity, the dependence of the active and reactive components of the impedance in the frequency range from 50 kHz to 2 GHz, the Smith chart of the S11 parameter in the frequency range from 50 kHz to 2 GHz, the standing wave ratio, the change in the logarithmic magnitude and the spectra of the output signal of the self-oscillating parametric humidity sensor in the LTE-800 Downlink frequency range.
4. The sensitivity of the developed self-oscillating parametric humidity sensor in the range of humidity change from 30% to 99% has a value from 332.8 kHz/% to 130.2 kHz/%.

References

[1] Assaf T.: A Frequency Modulation-Based Taxel Array: A Bio-Inspired Architecture for Large-Scale Artificial Skin. Sensors 21, 2021, 1−17.
[2] di Benedetto M.-G. et al.: Analysis of NB-IoT technology towards massive Machine Type Communication. University Sapienza di Roma, Roma 2018.
[3] Brown P.: Sensors and actuators: technology and applications. Library Press, New York 2017.
[4] Bury O. A. et al.: Gas sensors on nanostructures: current state and research prospects. Bulletin of the National University "Lviv Polytechnic", Series: Radioelectronics and telecommunications 885, 2017, 113–131.
[5] Czubenko M. et al.: Simple Neural Network for Collision Detection of Collaborative Robots. Sensors 21, 2021, 4235.
[6] Feng Y. et al.: Enhanced Frequency Stability of SAW Yarn Tension Sensor by Using the Dual Differential Channel Surface Acoustic Wave Oscillator. Sensors 23(1), 2023, 464.
[7] Galka A. G. et al.: Microwave Cavity Sensor for Measurements of Air Humidity under Reduced Pressure. Sensors 23(3), 2023, 1498.
[8] Grieshaber D. et al.: Electrochemical Biosensors − Sensor Principles and Architectures. Sensors 8, 2008, 1400−1458.
[9] Grundmann M.: The Physics of Semiconductors. Springer-Verlag, Berlin Heidelberg 2006.
[10] Hang L. et al.: Design and Implementation of Sensor-Cloud Platform for Physical Sensor Management on CoT Environments. Electronics 7, 2018, 1−25.
[11] Lepikh Ya. I. et al.: Intelligent measuring systems based on new generation microelectronic sensors. Astroprint, Odessa 2011.
[12] Manea G. et al.: Integration of sensor networks in cloud computing. UPB Sci. Bull., Series C 78, 2016.
[13] Nagarai A.: Introduction to Sensors in IoT and Cloud Computing Applications. Bentham Science Publishers, Bangalore 2021.
[14] Nelyudov I. Sh. et al.: Automatic control of technological objects. NAU, Kyiv 2018.
[15] Osadchuk A. V. et al.: Mathematical Model Radio-Measuring Frequency Transducer of Optical Radiation Based on MOS Transistor Structures with Negative Differential Resistance. Journal of Nano- and Electronic Physics 13(4), 2021, 04001.
[16] Osadchuk A. V. et al.: Microelectronic Transducer Gas Concentration based on MOSFET with Active Inductive Element. Przegląd Elektrotechniczny 4, 2019, 237−241.
[17] Osadchuk A. V., Osadchuk V. S.: Frequency Transducers of Gas Concentration Based on Transistor Structures with Negative Differential Resistance. Sidorenko A., Hahn H. (eds): Functional Nanostructures and Sensors for CBRN Defence and Environmental Safety and Security. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht 2020.
[18] Osadchuk V. S. et al.: Reactive properties of transistors and transistor circuits. Universum-Vinnytsia, Vinnytsia 1999.
[19] Osadchuk V. S. et al.: Temperature transducer based on a metal-pyroelectric-semiconductor structure with negative differential resistance. Proc. SPIE 10808, 2018, 108085D.
[20] Sainju P. M.: LTE Performance analysis on 800 and 1800 MHz Bands. Tampere University of Technology. Tampere 2012.
[21] Sze S. M. et al.: Physics of Semiconductor Devices. Wiley-Interscience, Hoboken 2007.
[22] Yang H. et al.: A Study on the Gas/Humidity Sensitivity of the High-Frequency SAW CO Gas Sensor Based on Noble-Metal-Modified Metal Oxide Film. Sensors 23(5), 2023, 2487.
[23] https://datasheetspdf.com/datasheet/HR202.html
[24] LTspice XVII. Analog Devices Corporation, 2018.
[25] SPICE Device Models and Simulation Examples. Oxford University Press, 2020.

Ph.D. Iaroslav Osadchuk
e-mail: osadchuk.j93@gmail.com

Candidate of Technical Sciences, associate professor of Information Radioelectronic Technologies and Systems of Vinnytsia National Technical University. Author of more than 180 publications, including 6 monographs, 60 patents for inventions and more than 100 scientific articles in professional journals, of which 27 are in scientometric databases Scopus and Web of Science.

http://orcid.org/0000-0002-5472-0797

Prof. Vladimir Osadchuk
e-mail: osadchuk.vs38@gmail.com

Doctor of Technical Sciences, Professor of Information Radioelectronic Technologies and Systems of Vinnitsa National Technical University, Honored Worker of Science and Technology of Ukraine, Academician of the Academy of Engineering Sciences of Ukraine. Author of more than 900 publications, including 22 monographs, 14 textbooks, more than 350 copyright certificates and patents for inventions and more than 550 scientific articles in professional journals, of which 40 are in scientometric databases Scopus and Web of Science.

http://orcid.org/0000-0002-3142-3642

Prof. Oleksandr Osadchuk
e-mail: osadchuk.av69@gmail.com

Doctor of Technical Sciences, Professor, Head of the Department of Information Radioelectronic Technologies and Systems of Vinnitsia National Technical University, Academician of the Academy Metrology Ukraine. Author of over 900 publications, including 34 monographs, 17 textbooks, 300 patents for inventions, more than 500 scientific articles in professional journals, of which 69 are in the scientometric databases Scopus and Web of Science.

http://orcid.org/0000-0001-6662-9141

Ph.D. Lyudmila Krylik
e-mail: lyudmila.krylik@gmail.com

Candidate of Technical Sciences, associate professor of the Department for Computer Science of Vinnytsia National Technical University. Author of more than 150 publications, including 2 monographs, 12 textbooks, 60 patents for inventions of Ukraine and more than 80 scientific articles in professional journals, of which 6 are in scientometric database Scopus.

http://orcid.org/0000-0001-6642-754X