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Solid State Radio-Measuring Optical-Frequency Transducer of Gas Flow Rate

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The paper presents a study of a solid state radio-measuring optical-frequency transducer of gas consumption based on a transistor structure with a negative differential resistance. A mathematical model of a solid state radio-measuring optical-frequency flowmeter was developed, which made it possible to obtain the conversion function and the sensitivity equation. The solid state radio-measuring optical-frequency gas flowmeter is based on a transistor structure with a negative differential resistance, consisting of a HEMT field-effect transistor and a bipolar transistor with a passive inductive element. When replacing the passive inductance with an active inductive element, the transducer can be completely integrated. The operation of a solid state radio-measuring optical-frequency gas flowmeter is based on the interferometric method of refractometry of optically transparent liquids and gases. The negative differential resistance formed by the parallel connection of the impedance with the capacitive component on the collector-drain electrodes of the transistor structure and inductance leads to the occurrence of electrical oscillations in the oscillator circuit. Theoretical and experimental studies have shown that with an increase in gas consumption from 0 l/h to 4 l/h, the generation frequency decreases from 812.65 MHz to 811.62 MHz at a supply voltage of 3.3 V, and at a supply voltage of 3.8 V from 813.00 MHz to 811.80 MHz. It is shown that by choosing a constant voltage power supply mode, it is possible to obtain an almost linear dependence of the generation frequency on the gas flow rate and choose channels for transmitting measurement information. Studies have shown that the sensitivity of the developed device is 262 kHz/l/h. The obtained theoretical and experimental studies are in good agreement, the relative error does not exceed 2.5 %.

Keywords: solid state radio-measuring optical-frequency gas flowmeter, photosensitive transistor, negative differential resistance, frequency, interferometric refractometry.

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Introduction

At the present stage of development of solid-state electronics and scientific and technological progress, the main directions of development of micro- and nanoelectronics are to improve existing and create new methods and means of collecting, processing, storing and transmitting information on the one hand, and on the other - creating high-precision and sensitive systems automation and control for industry, transport, military equipment, medicine, household purposes, etc. [1, 4-8]. The first direction ensures the development and improvement of production microelectronic technology, intensive growth of labor productivity, ensuring compliance with the standards of sanitary and hygienic working conditions of personnel, and high quality of finished industrial products. That is why research and development of methods and instruments for measuring quantities of both electrical and non-electrical nature today is a relevant scientific direction [1, 2, 4-8].

Among the transducers of non-electrical quantities, an important place is occupied by transducers of the flow rate of gas and liquids, which recently have a wide range of applications. They are necessary for scientific research, for the control of technological processes, for the control of the operation of power plants, for the control of airplanes and spaceships. In addition, precision gas flow transducers are required in medical technology [9].

Therefore, an important task of modern

instrumentation and measuring technology is the choice of reliable methods for measuring the flow rate of gas and liquid in relation to various industries, the creation of radio measuring instruments of the required accuracy, stability and speed, as well as studying the effect on the measurement result of the entire set of factors accompanying the measuring process [10].

One of the new scientific directions in the construction of solid state radio-measuring transducers of gas consumption is research in the field of frequency flowmeters based on transistor structures with negative differential resistance. Solid state radio-measuring transducers of gas flow rate with a frequency output combine both simplicity and versatility that are inherent in analog devices, as well as high sensitivity, accuracy and noise immunity, which are typical for measuring transducers with a coded output signal [10-13].

The study of this scientific direction showed that the reactive properties and negative differential resistance are inextricably linked, and the multifunctionality and simplicity of radiomeasuring devices based on transistor structures with negative differential resistance is a promising direction in their construction and practical use. Also, the application of the principle of conversion "gas flow rate – frequency" based on transistor structures with negative differential resistance significantly reduces the cost of infocommunication-measuring devices and systems, and also allows to reduce the mass-dimensional characteristics of radio measuring gas flow transducers, to increase not only sensitivity, but also accuracy converting an informative signal to frequency [10-17].

The aim of the work is to develop and study a solid state radio-measuring optical-frequency transducer of gas consumption based on a transistor structure with negative differential resistance. To achieve this goal in the work, it is necessary to solve the following tasks: 1) analyze existing scientific sources and substantiate the advantages of using the reactive properties of semiconductor structures with negative differential resistance; 2) calculate the main characteristics of a solid state radio-measuring optical-frequency transducer of gas flow, which take into account the dependence of the reactive properties of semiconductor structures with negative differential resistance on the gas flow; 3) draw conclusions from the study.

I. Research methods

To create a solid state solid state radio-measuring optical-frequency transducer of gas flow rate, we use the interferometric method of refractometry of optically transparent liquids and gases, and a frequency transducer based on a transistor structure with a negative differential resistance was chosen as a photosensitive device.

Let's consider the principle of operation of the optical part of a gas flowmeter. To ensure high sensitivity and accuracy of measuring the gas flow rate, an additional mirror is introduced into the structure, which is located on the same optical axis with the semitransparent plates and the radiation source, and both mirrors are located outside the measuring chamber with gas, so that there are no objects in the medium under study. The optical-frequency gas flowmeter contains a radiation source, a container with the medium under study, semitransparent plates and two mirrors, which are located on the optical axes along the path of the optical beams, as well as a unit for measuring the optical path difference of the beams (frequency optical transducer). A pipeline with gas is used as a container with the medium under study, it is made with two pairs of holes symmetrically located relative to the pipeline axis and in the direction of flow, closed with optical glass plates, in addition, one more mirror is contained. The mirrors are located outside the pipeline, with the additional mirror and semitransparent plates located on the same optical axis with the radiation source.

II. Results and discussion

Figure 1 shows a diagram of a solid-state radio-measuring optical-frequency gas flow rate transducer. The solid-state radio-measuring gas flow rate transducer contains a light source 1, which is an AsGa light-emitting diode of the CQY36N type (wavelength 950 nm), a semitransparent plate 2 on the optical axis of the beam, a light beam 3, which is reflected from a semitransparent plate 2 and through optical glass plates 4, 5 hits the mirror 6, and the light beam 7 passes through the semitransparent plate 8 to the additional mirror 9 and through the optical glass plates 10, 11 hits the mirror 12, the rays reflected from the mirrors 6 and 12 fall into the unit for measuring the optical path difference (optical-

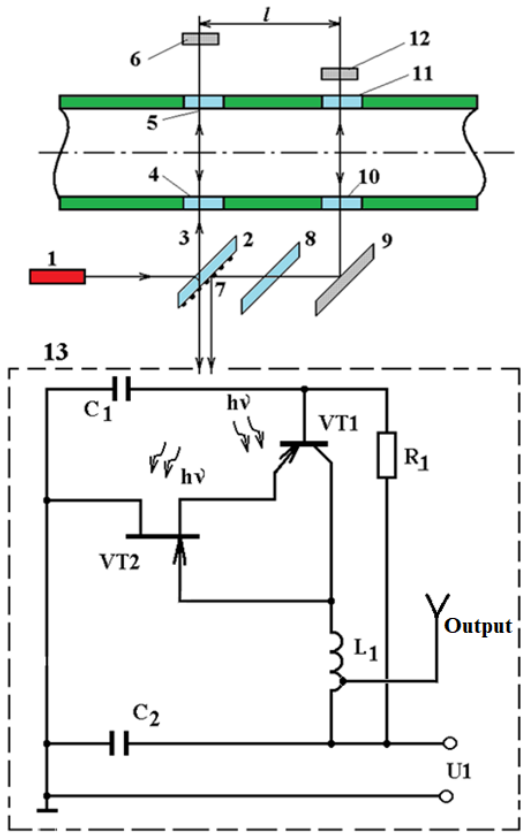

Fig. 1. Diagram of a radio-measuring optical-frequency transducer of gas consumption.

frequency transducer based on bipolar-field-effect transistor structure with negative differential resistance) 13 [18]. An additional mirror 9, as well as semitransparent plates 8 and 2 are placed on the same optical axis with the light source 1. In the optical-frequency gas flow meter, photosensitive bipolar and field-effect transistors are used as elements sensitive to optical radiation.

The optical path lengths that the first and second beams pass through the gas volume are different when the gas passes through the pipeline. Gas consumption is related to the pressure difference in two sections of the pipeline by the equation [18]:

$$Q = \frac{P_1 - P_2}{8\mu l}\pi R^4, \qquad (1)$$

where $P_1 - P_2$ is the pressure difference in two sections of the measuring chamber of the optical-frequency gas flowmeter; Q is gas consumption; l is the distance between the intersections of the flowmeter measuring chamber; μ is dynamic viscosity of the measured gas; R is the radius of the measuring chamber.

When using an interferometer, the maxima of the intensity of interfering waves in the measuring chamber of the transducer are observed when the following condition is met [18]:

$$(n_1 - n_2)2R = \lambda_0 k, \qquad (2)$$

where λ_0 is the wavelength of optical radiation; k = 0, 1, 2... is the coefficient determined by the unit for measuring the optical difference in the path of the beams in the measuring chamber of the optical-frequency transducer.

The dependence of the gas flow rate on the power of optical radiation is described by the expression:

$$Q = z \cdot P \cdot k, \qquad (3)$$

where z is the proportionality coefficient.

The proportionality coefficient is determined by the method of calibrating the flow rates to the number and describes the ratio of the optical difference in the path of the rays with the wavelength of light, that is, the indication of the unit for measuring the optical difference in the path of the rays.

The solid state radio-measuring optical-frequency converter of gas consumption is realized on the basis of a design consisting of a HEMT field-effect transistor (ATF35143) and a bipolar transistor (BFT93). In this design, both field-effect and bipolar transistors act as a photosensitive element (Fig. 1). It has been shown theoretically and experimentally that there is a negative differential resistance on the collector-drain electrodes of the proposed transistor structure, which corresponds to a falling section on the current-voltage characteristic [9, 11, 12]. The solid state radio-measuring optical-frequency transducer of gas consumption is powered from a constant voltage source U_1. The electric circuit R_1C_1 creates an additional positive feedback of the output with the input, and also with the help of the resistance R_1, the direct current of the bipolar transistor VT1 is controlled, and the capacitance C_1 determines the

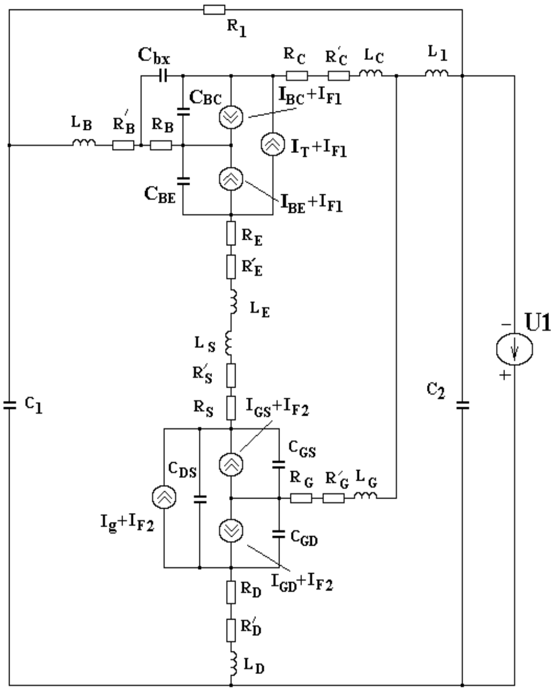

Fig. 2. Equivalent transducer circuit based on HEMT field-effect transistor and bipolar transistor.

capacitive component of the impedance of the transistor structure. Capacitance C_2 performs a blocking role, that is, it protects the DC source U_1 from extremely high frequency currents. The oscillating circuit is formed by passive inductance L_1 and the capacitive component of the impedance of the transistor structure, which exists on the collector-drain electrodes of the bipolar and field-effect transistors. When replacing the passive inductance with an active inductive element, the transducer can be completely integrated.

To study the behavior of a solid state radio-measuring optical-frequency transducer of gas consumption in a dynamic mode, it is necessary to obtain the dependence of the active and reactive components of the impedance at the collector-drain electrodes of the transistor structure, the generation frequency, the conversion function and sensitivity from the action of optical radiation and, ultimately, from the gas consumption. Calculations are made on the basis of the equivalent circuit of bipolar and field-effect HEMT transistors (Fig. 2).

The current-voltage characteristic of a solid state radio-measuring transducer based on a HEMT field-effect transistor and a bipolar transistor has a section of negative resistance, which makes it possible to compensate for energy losses in the oscillatory circuit. The oscillatory circuit is formed by the equivalent collector-drain capacitance of the structure and external inductance. The transformation function is calculated from a system of equations, which are based on the equivalent circuit of the converter (Fig. 3). The system of Kirchhoff equations, according to the directions of the loop currents, has the form:

$$\left.\begin{aligned}
&U_1 = Z_{16}(i_1 + i_2),\\
&0 = (Z_8 + Z_{16} + Z_{15} + Z_{13} + Z_{14})i_2 - Z_8 i_7 + Z_{16} i_1 - Z_{15} i_4 + Z_{13} i_6 + Z_{14} i_3 + Z_{13}(I_{gd} - I_{gs} - I_g),\\
&0 = (Z_7 + Z_6 + Z_4 + Z_9 + Z_{10} + Z_{12} + Z_{14})i_3 + Z_7 i_7 - Z_6 i_5 + Z_6(-I_{bc} + I_{be} + I_T) + Z_4 i_4 + Z_4(-I_{bc} + I_{be} + I_T) +\\
&+(Z_9 + Z_{10})i_4 - Z_{12} i_6 + Z_{12}(-I_{gd} + I_{gs} + I_g) + Z_{14} i_2,\\
&0 = (Z_1 + Z_3 + Z_4 + Z_9 + Z_{10} + Z_{11} + Z_{15} + Z_{17})i_4 - Z_1 i_7 + Z_4(-I_{bc} + I_{be} + I_T) + (Z_9 + Z_{10})i_3 + Z_{11} i_6 +\\
&+Z_{11}(-I_{gd} + I_{gs} + I_g) - Z_{15} i_2 + Z_3 i_5 + Z_3 i_3,\\
&0 = (Z_5 + Z_3 + Z_6)i_5 + Z_5 i_7 + Z_3 i_4 - Z_6 i_3 + Z_6(I_{bc} - I_{be} - I_T),\\
&0 = (Z_{11} + Z_{13} + Z_{12})i_6 + Z_{11}(-I_{gd} + I_{gs} + I_T) + Z_{11} i_4 + Z_{13} i_2 + Z_{13}(I_{gd} - I_{gs} - I_g) - Z_{12} i_3 + Z_{12}(I_{gd} - I_{gs} - I_g),\\
&0 = (Z_8 + Z_7 + Z_5 + Z_1 + Z_2)i_7 - Z_8 i_2 + Z_7 i_3 + Z_5 i_5 - Z_1 i_4,
\end{aligned}\right\}, \qquad (4)$$

where $Z_2 = R_1$, $Z_1 = R'_B + j\omega L_B$, $Z_3 = R_B$, $Z_4 = -j/(\omega C_{BE})$, $Z_5 = -j/(\omega C_{bx})$, $Z_6 = -j/(\omega C_{BC})$, $Z_7 = R_C + R'_C + j\omega L_C$, $Z_8 = j\omega L_1$, $Z_9 = R_E + R'_E + j\omega L_E$, $Z_{10} = R_S + R'_S + j\omega L_S$, $Z_{11} = -j/(\omega C_{DS})$, $Z_{12} = -j/(\omega C_{GS})$, $Z_{13} = -j/(\omega C_{GD})$, $Z_{14} = R_G + R'_G + j\omega L_G$, $Z_{15} = R_D + R'_D + j\omega L_D$, $Z_{16} = -j/(\omega C_2)$, $Z_{17} = -j/(\omega C_1)$.

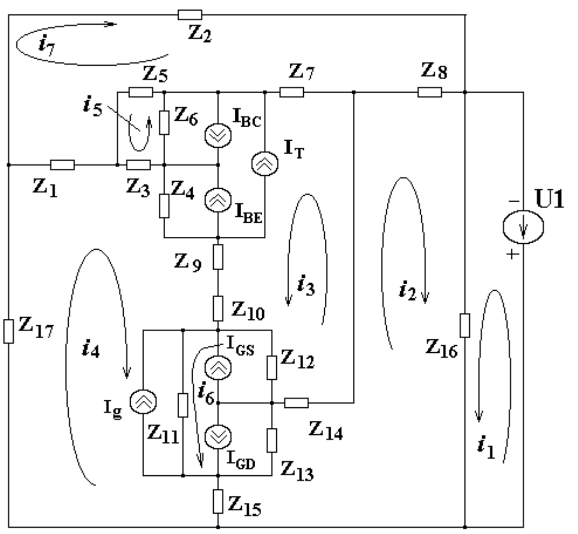

Fig. 3. Converted equivalent circuit of the transducer based on HEMT field-effect transistor and bipolar transistor.

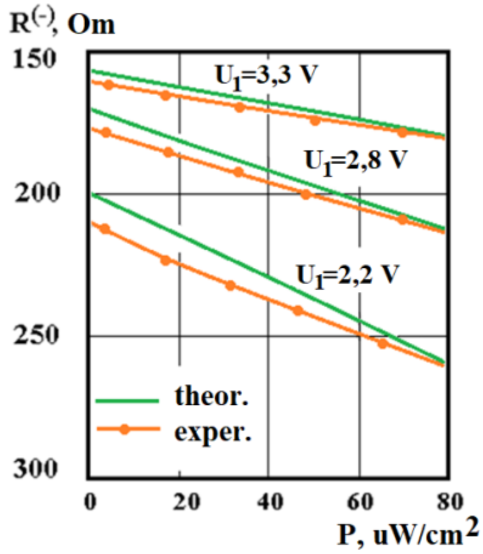

Fig. 4. Theoretical and experimental dependences of the active component from the radiation power with different supply voltages.

The solution of the system of equations was carried out by the Gauss method on a personal computer using the "Matlab 9.4" software package [19]. The parameters of the transistors, on the basis of which the photosensitive structure is built, as well as the parameters of the equivalent circuit of the converter, were determined from [20-23]. Calculations of the impedance of the frequency transducer structure make it possible to obtain all the necessary metrological characteristics of a solid state radio-measuring optical-frequency gas flowmeter.

Figure 4 shows the theoretical and experimental dependences of the active component of the impedance on the radiation power with different supply voltages. The analysis shows that there is a slight increase in the negative differential resistance with an increase in the optical radiation power from 0 μW/cm^2 to 80 μW/cm^2 with supply voltages of 3.3 V. With a decrease in the supply voltage to 2.2 V, a greater increase in the negative differential resistance is observed to 65 Ohm from the change in the radiation power in the range from 0 μW/cm^2 to 80 μW/cm^2. Figure 5 shows the dependence of the negative differential resistance on the supply voltage at various values of the optical radiation power. An increase in the supply voltage of more than 3.5 V leads to a lower dependence of the active resistance on the power of the light flux.

The theoretical and experimental dependences of the reactive component of the impedance of the solid state radio-measuring optical-frequency transducer of the gas flow rate on the optical radiation power are shown in Fig. 6. The reactive component has a capacitive nature and its value in absolute value decreases almost linearly with an increase in the power of light radiation.

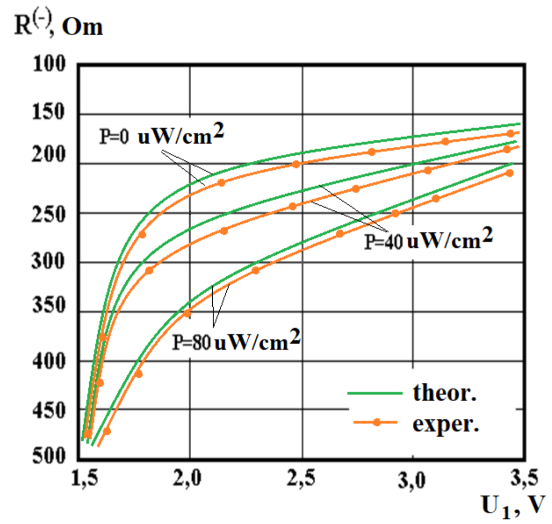

Fig. 5. Dependence of the active component of the impedance on the supply voltage with different radiation powers.

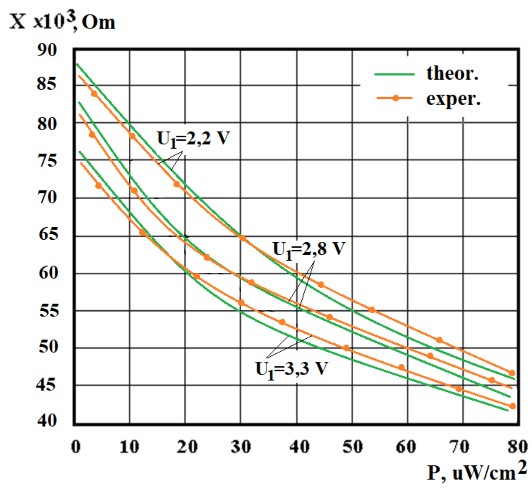

Fig. 6. Theoretical and experimental dependence of the reactive component on the power of optical radiation.

To determine the conversion function, it is necessary to find the dependence of the generation frequency on the gas flow rate. This can be done by solving the system of equations (4), which is compiled for alternating current based on the equivalent circuit (Fig. 3). When dividing the impedance into real and imaginary components, it is easy to determine the equivalent capacitance of the oscillatory circuit, which depends on the power of the incident radiation and, accordingly, on the gas flow rate. The transformation function in this case is:

$$F_0=\frac{1}{2}\frac{\sqrt{\dfrac{C_{be}(Q)C_{ds}(Q)C_2+C_{bc}(Q)C_{ds}(Q)C_2+C_{bc}(Q)C_{be}(Q)C_2+C_{bc}(Q)C_{be}(Q)C_{ds}(Q)}{LC_{bc}(Q)C_{be}(Q)C_{ds}(Q)C_2}}}{\pi}. \tag{5}$$

Figure 7 shows the dependence of the generation frequency on the gas flow rate. The largest range of variation of the conversion function can be obtained if the wavelength of the optical radiation is 0.95 μm. Experimental studies have shown that the generation frequency increases from 810.15 MHz to 813.75 MHz if the voltage increases from 1.4 V to 3.8 V. The sensitivity equation is determined based on expression (5) and is described by the formula:

$$\begin{aligned}S_Q=\frac{1}{4}\Bigg(\Bigg(\Bigg(&\left(\frac{\partial C_{be}(Q)}{\partial Q}\right)C_{ds}(Q)C_2+C_{be}(Q)\left(\frac{\partial C_{ds}(Q)}{\partial Q}\right)C_2+\left(\frac{\partial C_{bc}(Q)}{\partial Q}\right)C_{ds}(Q)C_2+C_{bc}(Q)C_2\left(\frac{\partial C_{ds}(Q)}{\partial Q}\right)+\\&+\left(\frac{\partial C_{bc}(Q)}{\partial Q}\right)C_{be}(Q)C_2+\left(\frac{\partial C_{be}(Q)}{\partial Q}\right)C_{bc}(Q)C_2+\left(\frac{\partial C_{bc}(Q)}{\partial Q}\right)C_{be}(Q)C_{ds}(Q)+\left(\frac{\partial C_{be}(Q)}{\partial Q}\right)C_{bc}(Q)C_{ds}(Q)+\\&+\left(\frac{\partial C_{ds}(Q)}{\partial Q}\right)C_{bc}(Q)C_{be}(Q)\Bigg)/\left(LC_{bc}(Q)C_{be}(Q)C_{ds}(Q)C_2\right)-\frac{A_1\left(\dfrac{\partial C_{bc}(Q)}{\partial Q}\right)}{LC_{bc}^2(Q)C_{be}(Q)C_{ds}(Q)C_2}-\\&-\frac{A_1\left(\dfrac{\partial C_{be}(Q)}{\partial Q}\right)}{LC_{bc}(Q)C_{be}^2(Q)C_{ds}(Q)C_2}-\frac{A_1\left(\dfrac{\partial C_{ds}(Q)}{\partial Q}\right)}{LC_{bc}(Q)C_{be}(Q)C_{ds}^2(Q)C_2}\Bigg)\Bigg/\left(\pi\sqrt{\frac{A_1}{LC_{bc}(Q)C_{be}(Q)C_{ds}(Q)C_2}}\right)\end{aligned}, \tag{6}$$

where $A_1=C_{be}(Q)C_{ds}(Q)C_2+C_{bc}(Q)C_{ds}(Q)C_2+C_{bc}(Q)C_{be}(Q)C_2+C_{be}(Q)C_{ds}(Q)C_{bc}(Q)$.

Figure 8 shows the theoretical and experimental dependence of the output voltage on the supply voltage. The output voltage rises from 1.75 V to almost 2.78 V with an increase in the supply voltage from 1.6 V to 3.3 V. The sensitivity of the device is from 296 kHz/l/h to 262 kHz/l/h (Fig. 9). The temperature stable section of the operation of the radio-measuring optical-frequency converter of gas consumption lies in the temperature range from -40 °C to + 80 °C.

The frequency 812-814 MHz is selected according to the EN 300 466 standard, or the European standard ECC DEC (01)02. The theoretical and experimental dependences of the generation frequency of the radio-measuring optical-frequency flowmeter showed that with

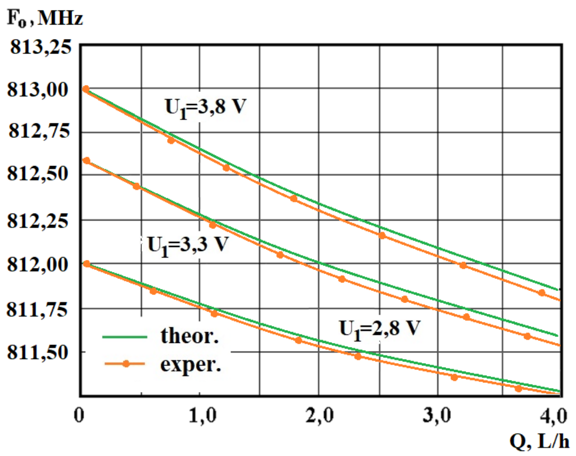

Fig. 7. Dependence of the generation frequency on the optical radiation power.

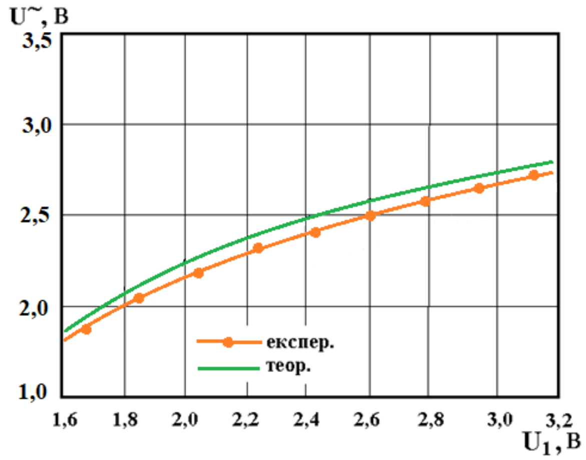

Fig. 8. Dependence of the output AC voltage on the supply voltage.

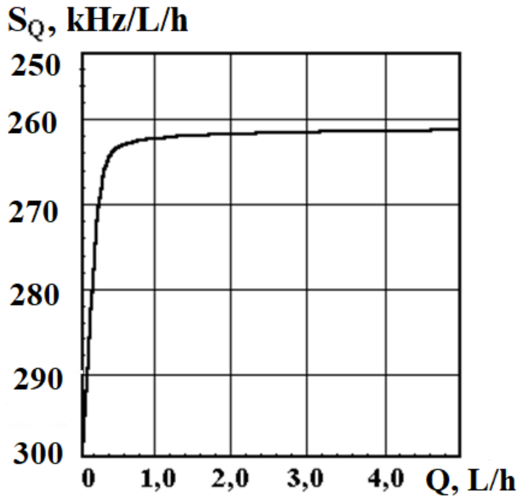

Fig. 9. Dependence of the sensitivity of the radio-measuring optical-frequency flowmeter on the gas flow rate.

an increase in gas consumption from 0 l/h to 4 l/h the generation frequency decreases from 812.65 MHz to 811.62 MHz at a supply voltage of 3.3 V, and at a supply voltage of 3.8 V from 813.00 MHz to 811.80 MHz. Studies have shown that by choosing a constant voltage power supply mode, it is possible to obtain a linear dependence of the generation frequency on the gas flow rate and select channels for transmitting measurement information. The optimum supply voltage is 3.3 V, at which there is the smallest change in the generation frequency in the temperature range from 20 °C to 80 °C. Experimental and theoretical studies have shown that the sensitivity of the developed device is 262.5 kHz/l/h (Fig. 9).

Fig. 10 and Fig. 11 show screenshots from the SDRSharp program with a receiver based on

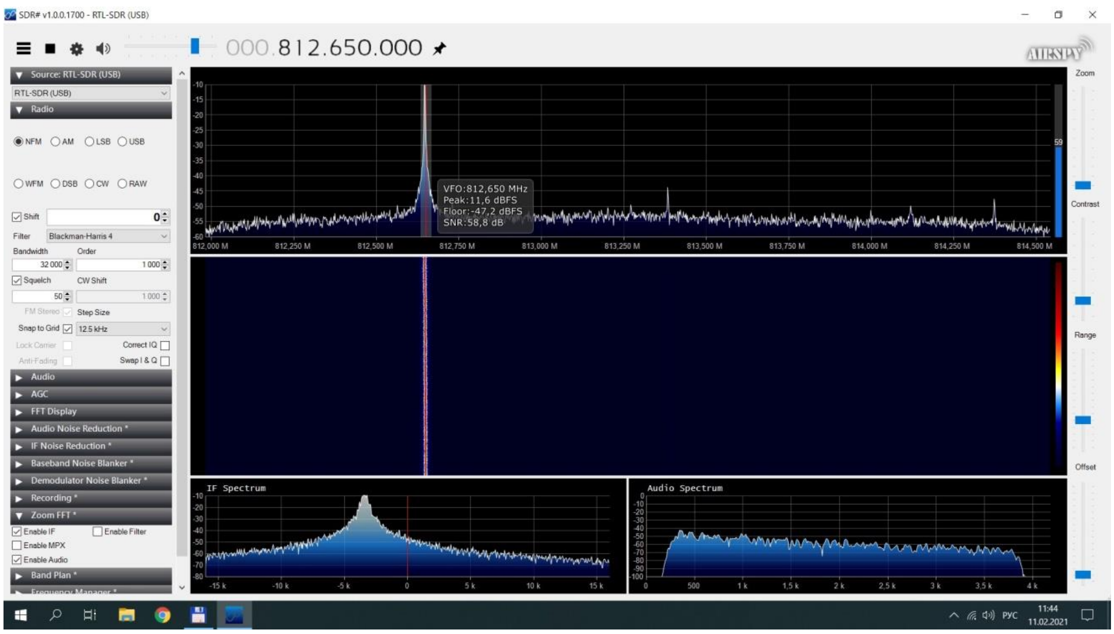

Fig. 10. The transmission spectrum of the radio-measuring optical-frequency flowmeter without changing the gas flow.

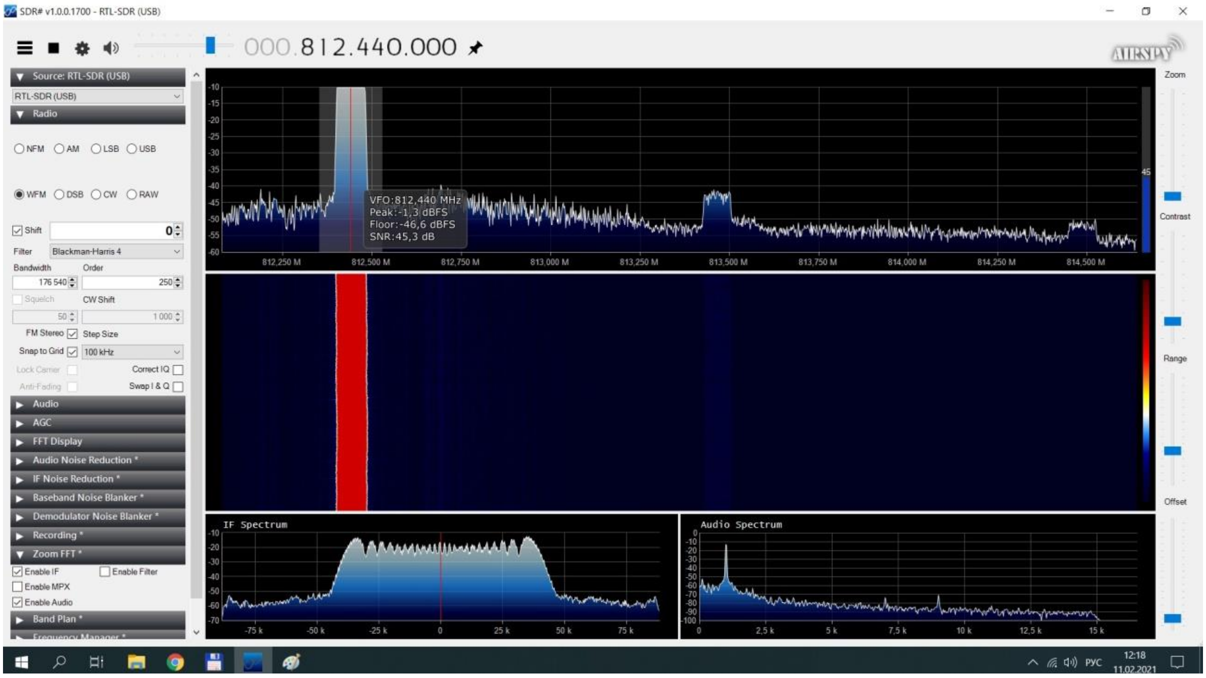

Fig. 11. The transmission spectrum of the radio-measuring optical-frequency flowmeter when the gas flow rate changes.

RTL2832U + R820T [24, 25]. The sampling rate (receiver bandwidth) is selected at 2.5 MHz. The larger the value, the wider we will see the bandwidth on the spectrum analyzer. Bandwidth selection is usually based on computer performance. The wider the bandwidth, the more resources must be used for the program. For example, the bandwidth on a computer with a Core i5 processor and 16 gigabytes of RAM is 2.5 MSPS. As can be seen from Fig. 10, the width of the transmission spectrum of the optical-frequency flowmeter without changing the gas flow rate is 2 kHz at a frequency of 812.650 MHz with a supply voltage of 3.3 V. Figure 11 shows the spectrum of the radio-measuring optical-frequency gas flow rate converter at gas flow rates 0.8 l/h and the transmission spectrum width increases to 70 kHz. This frequency modulation method allows to increase the noise immunity by 2.5 times and increase the transmission range at minimum transmission power.

Conclusions

A mathematical model of a solid state radio-measuring optical-frequency transducer of gas consumption was developed, which made it possible to obtain analytical dependences of the conversion function and the equation of the device's sensitivity. A design of a gas flowmeter based on a transistor structure with a negative differential resistance, which consists of a HEMT field-effect transistor and a bipolar transistor with a passive inductive element, is proposed. The operation of a solid state radio-measuring optical-frequency gas flowmeter is based on the interferometric method of refractometry of optically transparent liquids and gases. Using the Matlab environment, the main parameters of the gas sensor were calculated and the adequacy of the developed mathematical model was proved. It was found that there are periodic oscillations at the output of a solid state radio-measuring optical-frequency flowmeter, the frequency of which changes with a change in the gas flow rate. Theoretical and experimental studies have shown that with an increase in the gas consumption from 0 l/h to 4 l/h, the generation frequency decreases from 812.65 MHz to 811.62 MHz at a supply voltage of 3.3 V, and at a supply voltage of 3.8 V from 813.00 MHz to 811.80 MHz. It is shown that by choosing a constant voltage supply mode, it is possible to obtain a linearvdependence of the generation frequency on the gas flow rate and select channels for transmitting measurement information. Studies have shown that the sensitivity of the developed device is 262 kHz/l/h. The obtained theoretical and experimental studies are in good agreement, the relative error does not exceed 2.5 %.

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Твердотільний радіовимірювальний оптико-частотний перетворювач витрат газу

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В роботі представлено дослідження твердотільного радіовимірювального оптико-частотного перетворювача витрат газу на основі транзисторної структури з від'ємним диференційним опором. Розроблено математичну модель твердотільного радіовимірювального оптико-частотного витратоміра, яка дозволила отримати функцію перетворення та рівняння чутливості. Твердотільний радіовимірювальний оптико-частотний витратомір газу створено на основі транзисторної структури з від'ємним диференційним опором, що складається з HEMT польового транзистора і біполярного транзистора з пасивним індуктивним елементом. При заміні пасивної індуктивності на активний індуктивний елемент перетворювач повністю можна виконати в інтегральному вигляді. В основі роботи твердотільного радіовимірювального оптико-частотного витратоміру газу лежить інтерферометричний спосіб рефрактометрії оптично прозорих рідин і газів. Від'ємний опір, утворений паралельним включенням повного опору з ємнісною складовою на електродах колектор-стік транзисторної структури та індуктивності, приводить до виникнення електричних коливань в контурі твердотільного автогенератора. Встановлено, що на виході твердотільного радіовимірювального оптико-частотного витратоміра існують періодичні коливання, частота яких змінюється зі зміною оптичного випромінювання, яке діє на фоточутливі транзистори. Теоретичні та експериментальні дослідження показали, що зі зростанням витрат газу від 0 л/год до 4 л/год зменшується частота генерації від 812,65 МГц до 811,62 МГц при напрузі живлення 3,3 В, а при напрузі живлення 3,8 В від 813,00 МГц до 811,80 МГц. Показано, що вибором режиму живлення з постійної напруги, можна отримати практично лінійну залежність частоти генерації від витрат газу та вибирати канали для передачі вимірювальної інформації. Проведені дослідження показали, що чутливість розробленого пристрою складає 262 кГц/л/год. Отримані теоретичні та експериментальні дослідження мають гарний збіг, відносна похибка не перевищує 2,5 %.

Ключові слова: твердотільний радіовимірювальний оптико-частотний витратомір газу, фоточутливий транзистор, від'ємний диференціальний опір, частота, інтерферометричний спосіб рефрактометрії.