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# Optical-frequency gas flow meter on the basis of transistor structures with negative differential resistance

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## ABSTRACT

The article investigated the optical-frequency gas flow meter based on a transistor structure with negative differential resistance (NDR). A schematic diagram and design of an optical-frequency gas flow transducer that operates in the microwave range (0.85 to 1.5 GHz), which consists of a bipolar and field-effect transistor with a Schottky barrier, is proposed as a photosensitive element using a photoresistor. A mathematical model of an optical-frequency gas flow meter based on a transistor structure with negative differential resistance has been developed, which allows one to obtain the main characteristics of the transducer in a wide frequency range. Theoretically and experimentally, the possibility of controlling both the reactive component and the negative differential resistance from changes in control voltage and power is shown, it extends the functionality of optical transducers and allows linearization of the conversion function within (0.1 - 0.2)%. Experimental studies have shown that the greatest sensitivity and linearity of the conversion function of an optical-frequency gas flow transducer lies in the range from 3 V to 3.5 V. The sensitivity of the developed optical-frequency gas flow transducer based on a transistor structure with NDR is 146 kHz/liter/hour, and the measurement error is ± 1.5%.

**Keywords:** optical frequency transducer, flow meter, negative differential resistance, reactive properties.

## 1. INTRODUCTION

Further development of radio electronics requires more advanced optical gas flow meters [1,2,3]. Using the photoreactive effect and the negative resistance of semiconductor sensitive elements can increase the sensitivity [4,5] and accuracy of the conversion of optical signals [6,7,8]. Structurally, optical gas flow meters with a frequency output are performed in the form of an integrated hybrid circuit consisting of a gallium arsenide-field transistor with a Schottky barrier and a bipolar transistor. In this structure, a photoresistor acts as a photosensitive element. To study the properties of optical gas flow meters with a frequency output, it is necessary to consider the mechanism of interaction of optical radiation with a photosensitive element, to develop a mathematical model of an optical transducer that takes these effects into account. And on the other hand, on the basis of a mathematical model, it is necessary to obtain the basic characteristics of the transducer, the dependence of the active and reactive components of the impedance, the generation frequency on optical radiation and power modes [9,10,11]. These issues are addressed in this paper.

## 2. MATHEMATICAL MODEL

To create radio-measuring optical gas flow meters, we use the interferometric method of refractometry of optically transparent liquids and gases, and a frequency transducer based on a transistor structure with negative differential resistance is used as a photosensitive element [4,5,10].

Consider the principle of operation of the optical part of the gas flow meter. To ensure high sensitivity and accuracy of

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measuring the gas flow, an additional mirror was introduced into the design, located on the same optical axis as translucent plates and a radiation source, both mirrors being located outside the gas container, so that there are no objects in the medium under study. A device for measuring gas flow contains a radiation source, a container with the medium under study, translucent plates and two mirrors that are located on the optical axes along the optical rays, as well as a node for measuring the optical difference in the path of the rays (optical-frequency transducer). As a container with the medium under study, a gas pipeline is used, made with two pairs of holes that are symmetrically located relative to the axis of the pipeline and in the direction of flow, which are closed by optical glass plates, in addition, another mirror is additionally contained. Mirrors are located outside the pipeline, with an additional mirror and translucent plates placed on the same optical axis as the radiation source.

Figure 1 shows a diagram of an optical gas flow meter. The device contains a light source 1, a translucent plate 2 on the optical axis of the beam, a light beam 3, which is reflected from the translucent plate 2 and through optical glass plates 4, 5 enters the mirror 6. The light beam 7 passes through the translucent plate 8 to the additional mirror 9 and through the optical glass plates 10, 11 it enters the mirror 12, the rays reflected from the mirrors 6 and 12 fall into the measuring unit of the optical difference in the path of the rays (a frequency transducer based on a transistor structure with negative resistance) 13. Moreover, an additional mirror 9, translucent plates 8 and 2 are placed on the same optical axis with the light source 1.

The device operates as follows. The light beam from the light source 1 falls onto the translucent plate 2, one half of the incident light flux 3 is reflected by the translucent plate 2 in the direction of the mirror 6, the second half 7 passes through the translucent plate 8 and propagates in the direction of the additional mirror 9. beam 3 passes through the optical glass plate 4 and 5, reflected from the mirror 6 returns to the translucent plate 2, passing twice through the gas volume, characterized by pressure p1, refractive index n1. Then the beam 3 is rotated and passing through the translucent plate 2, propagates in the direction of the measuring unit of the optical path difference (frequency transducer based on a transistor structure with negative resistance) 13. The beam 7 is reflected from the additional mirror 9, passes through the optical glass plates 10 and 11 reflected from the mirror 12, passing twice through the gas volume, characterized by pressure p2, refractive index n2, reflected from the additional mirror 9 and returned to the translucent layer otherwise 2. Beam 7, reflected from the translucent plate 2, propagates in the direction of the measuring unit of the optical difference in the path of the rays (frequency transducer based on a transistor structure with negative resistance) 13. Subject to coherence conditions, the beams 3 and 7 will interfere. The result of interference depends on the optical difference in the path of the rays from the translucent plate 2 to the mirrors 6 and 12 and vice versa. Because beam 3 passes through the thickness of the translucent plate 2 times, and beam 7 only once, an additional translucent plate 8 is introduced into the flow meter design to compensate for the resulting optical travel difference.

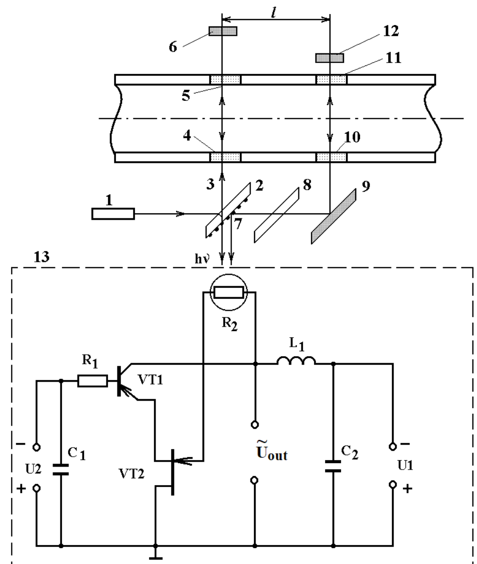


Fig. 1. The electrical circuit of a gas flow meter based on bipolar and field-effect transistors

The optical lengths of the path that the first and second rays pass through the gas volume are different when the gas passes through the pipeline. The gas flow rate is related to the pressure difference in the two sections of the pipeline by the equation

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

where $Q$ is the gas flow rate; $P_1 - P_2$ is pressure difference in two sections of the pipeline; $\mu$ is dynamic viscosity of the gas; $l$ is distance between intersections; $R$ is radius of the pipeline.

The equation of state of an ideal gas has the form

$$p = N \cdot k_0 \cdot T ,$$

where $N$ is the number of molecules per unit volume of a substance; $k_0$ is Boltzmann constant; $T$ is absolute temperature.

The refractive index of a gas is

$$n^2 = 1 + \frac{N}{\varepsilon_0}\sum_K \frac{e^2 / m}{\omega_{OK}^2 + \omega^2} ,$$

where $n$ is the refractive index of the gas; $\varepsilon_0$ is dielectric constant of vacuum; $e$ is electron charge; $m$ is mass of an electron; ( $OK$ –natural frequencies of electron vibrations); $\omega$ is frequency of light radiation.

The difference in the optical path of rays 3 and 7 is determined by the formula

$$L = (n_1 - n_2)2R .$$

When using an interferometer, the maxima of the intensity of interfering waves are observed under the following condition

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

where $\lambda_0$ is the radiation wavelength; $k$ = 0, 1, 2 ... is determined by the measuring unit of the optical difference in the path of the rays.

Thus, the dependence of the gas flow on the optical radiation power has the form

$$Q = z \cdot P \cdot k ,$$

where $z$ is the coefficient of proportionality.

The difference in the path of the rays is proportional to the unit of measurement of gas flow ($m^3$/s). The proportionality coefficient is determined by calibrating the gas flow rate into a number expressing the ratio of the optical difference in the path of the rays with the wavelength of light, that is, the indication of the measuring unit of the optical difference in the path of the rays. The measurement result is presented in $m^3$/s.

Now we turn to the consideration of the optical-frequency gas flow transducer consisting of a gallium arsenide field transistor with a Schottky barrier and a bipolar transistor [11]. This structure is basic for the construction of the transducer in such a way that it provides an operating mode in the range of very high frequencies, which is very important for microwave electronics. The electrical circuit of the device is shown in Fig. 1. It has been theoretically and experimentally shown that there is a negative dynamic resistance on the collector-gate electrodes of the proposed structure, which corresponds to a decreasing section on the current-voltage characteristic [11, 12]. Figure 2 shows the static and dynamic volt-ampere characteristics of the optical-frequency gas flow transducer.

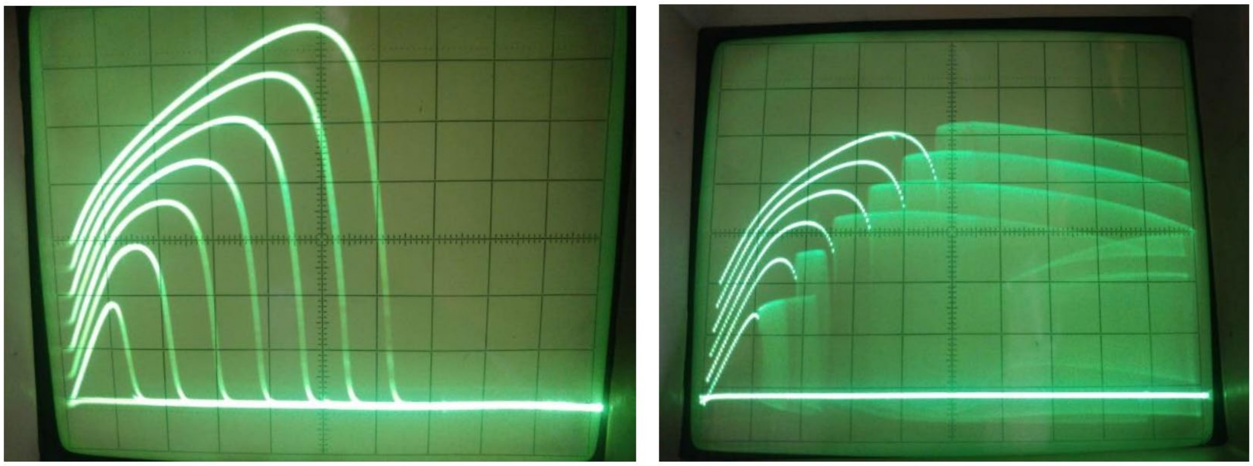

Fig. 2. The static and dynamic current-voltage characteristics of an optical-frequency gas flow transducer

The frequency transducer is powered by DC voltage sources $U_1$ and $U_2$. The circuit $R_1C_1$ creates an additional positive feedback between the output and the input, and also due to the resistance $R_2$, which is a photosensitive element, the collector of the bipolar transistor and the gate-drain circuit of the field effect transistor are powered. The capacitance $C_2$ carries out a blocking role, that is, it protects the DC source $U_1$ from currents of extremely high frequencies. The oscillating circuit is formed by a passive inductance $L_1$ and a capacitance that exists on the electrodes of the collector of bipolar and drain field-effect transistors.

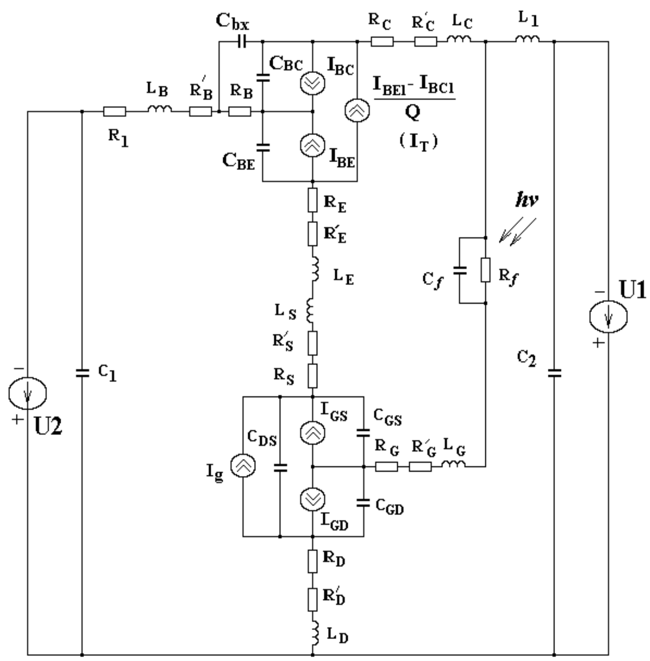


Fig. 3. The equivalent circuit of an optical-frequency gas flow transducer based on a bipolar and field effect transistors with a photosensitive resistor

To study the behavior of the frequency transducer of gas flow in dynamic mode, it is necessary to obtain the dependence of the active and reactive components of the impedance on the collector-drain electrodes of the structure, generation frequency, conversion function, and sensitivity on the action of optical radiation. The calculations are based on the equivalent circuit of bipolar and field-effect transistors that make up the optical-frequency transducer (Fig. 3).

The system of equations that describes the behavior of the transducer, and allows you to determine the impedance, has the form:

$$
\left.\begin{aligned}
&U_1 = Z_{16}(i_1 + i_2),\\
&0 = (Z_8 + Z_{16} + Z_{15} + Z_{13} + Z_{14} + Z_{18})i_2 + Z_{16}i_1 + Z_{14}i_3 + Z_{13}i_7 - Z_{15}i_4 + Z_{13}(I_{gd} - I_{gs} - I_g) + Z_{18}i_3,\\
&0 = (Z_7 + Z_6 + Z_4 + Z_9 + Z_{10} + Z_{12} + Z_{14} + Z_{18})i_3 - Z_6 i_6 + Z_6(-I_{bc} + I_{be} + I_T) + Z_4 i_4 +\\
&+Z_4(-I_{bc} + I_{be} + I_T) + (Z_9 + Z_{10})i_4 - Z_{12}i_7 + Z_{12}(-I_{gd} + I_{gs} + I_g) + Z_{14}i_2 + Z_{18}i_2,\\
&0 = (Z_1 + Z_2 + Z_3 + Z_4 + Z_9 + Z_{10} + Z_{11} + Z_{15} + Z_{17})i_4 + Z_4(-I_{bc} + I_{be} + I_T) + (Z_9 + Z_{10})i_3 + Z_{11}i_7 +\\
&+Z_{11}(-I_{gd} + I_{gs} + I_g) + Z_3 i_6 + Z_4 i_3 - Z_{15}i_2 - Z_{17}i_5,\\
&U_2 = Z_{17}(i_5 - i_4),\\
&0 = (Z_5 + Z_3 + Z_6)i_6 + Z_3 i_4 - Z_6 i_3 + Z_6(I_{bc} - I_{be} - I_T),\\
&0 = (Z_{11} + Z_{13} + Z_{12})i_7 + Z_{11}i_4 + Z_{11}(-I_{gd} + I_{gs} + I_g) - Z_{12}i_3 + Z_{12}(I_{gd} - I_{gs} - I_g) + Z_{13}i_2 + Z_{13}(I_{gd} - I_{gs} - I_g),
\end{aligned}\right\} \quad (1)
$$

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

$$Z_{15} = R_D + R'_D + j\omega L_D, \quad Z_{18} = \frac{R_f(P)}{1 + (\omega R_f(P)C_f)^2} - j\frac{\omega R_f^2(P)C_f}{1 + (\omega R_f(P)C_f)^2}.$$

The system of equations (1) is solved using the Gauss method on a personal computer in the software environment "Matlab 9.4". The values of the parameters of the equivalent circuit, which are necessary for the calculations, obtained from [8,9,10].

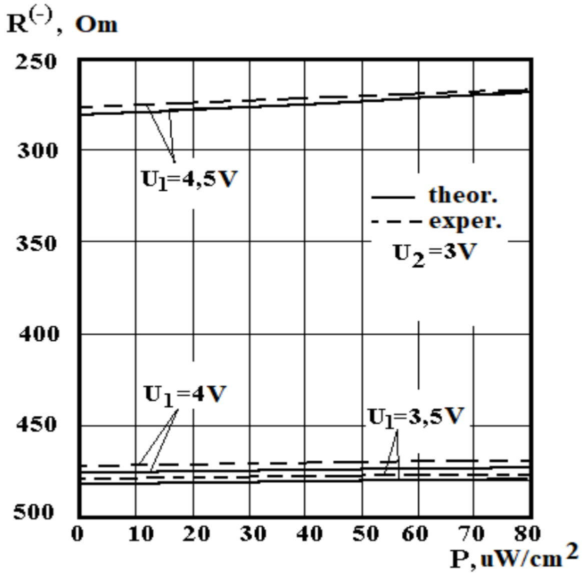


Fig. 4. Theoretical and experimental dependence of the active component on the power of optical radiation

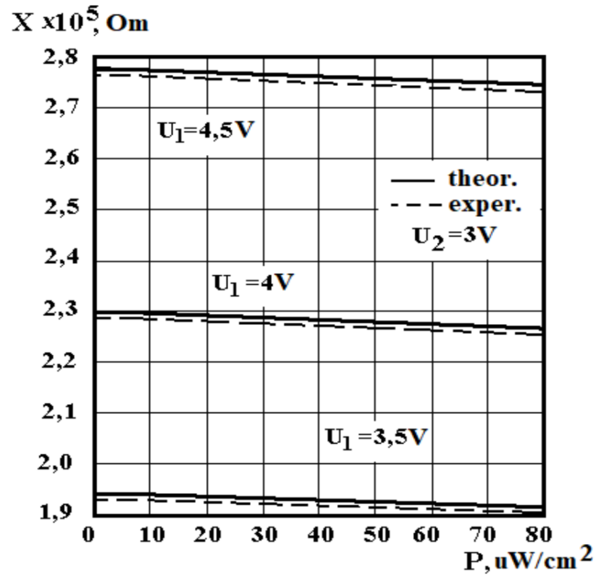


Fig. 5. Theoretical and experimental dependence of the reactive component on the power of optical radiation

Theoretical and experimental studies have shown that the active component takes a negative value, and the reactive component takes on a capacitive character. Connecting an external inductance to the collector-gate terminals of the structure at negative values [11–13] of the active component of the impedance, when energy losses in the oscillatory circuit are compensated, allows you to create an electric oscillator. During the action of light on the photosensitive resistor $R_1$, the active and reactive components of the impedance change, and this, in turn, changes the generation frequency [14,15].

Figure 4 shows the theoretical and experimental dependences of the active component of the impedance on the power of optical radiation at various values of the supply voltage of the structure. As the analysis of the given curves shows, there is an almost linear decrease in negative resistance with increasing optical radiation power, and the supply voltage determines the initial value of negative resistance. Figure 5 shows the experimental and theoretical dependences of the reactive component of the impedance on the power of optical radiation. It can be seen from the graph that the reactive component has a capacitive character and its modulo value decreases with increasing radiation power, and the reactive component decreases almost linearly with increasing radiation power from zero to 80μW/cm$^2$.

To determine the conversion function, it is necessary to find the dependence of the generation frequency on the incident radiation power. This can be done by solving the system of Kirchhoff equations, which is composed for alternating current based on the equivalent circuit (Fig. 3). The solution of the system of equations (1) allows us to obtain the value of the impedance at the collector-drain transducer electrodes. When dividing the impedance into real and imaginary components, it is easy to determine the equivalent capacitance of the oscillating circuit, which depends on the power of the incident light and, accordingly, on the gas flow rate. The conversion function in this case has the form:

$$F_0 = \frac{1}{4}\frac{\sqrt{2}\sqrt{\dfrac{R_f^2(Q)C_f^2 + C_{gd}R_f^2(Q)C_f - LC_{gd} - \sqrt{(R_f^2(Q)C_f^2 + C_{gd}R_f^2(Q)C_f - LC_{gd})^2 + 4LC_{gd}R_f^2(Q)C_f^2}}{LC_{gd}R_f^2(Q)C_f^2}}}{\pi} \qquad (2)$$

The sensitivity of the gas flow meter is determined by the formula:

$$S_Q = \frac{1}{4}\frac{\sqrt{2}\left(\dfrac{\partial R_f(Q)}{\partial Q}\right)\left(R_f^2(Q)C_f^2 - C_{gd}R_f^2(Q)C_f + \sqrt{A_1} + LC_{gd}\right)}{\pi R_f^2(Q)C_f\sqrt{A_1}\sqrt{-\dfrac{-R_f^2(Q)C_f^2 - C_{gd}R_f^2(Q)C_f + \sqrt{A_1} + LC_{gd}}{LC_{gd}R_f^2(Q)C_f^2}}}, \qquad (3)$$

where $A_1 = R_f^4(Q)C_f^4 + 2R_f^4(Q)C_f^4C_{gd} + 2LC_{gd}R_f^2(Q)C_f^2 + C_{gd}^2R_f^4(Q)C_f^4 - 2C_{gd}^2R_f^2(Q)C_fL + L^2C_{gd}^2$ .

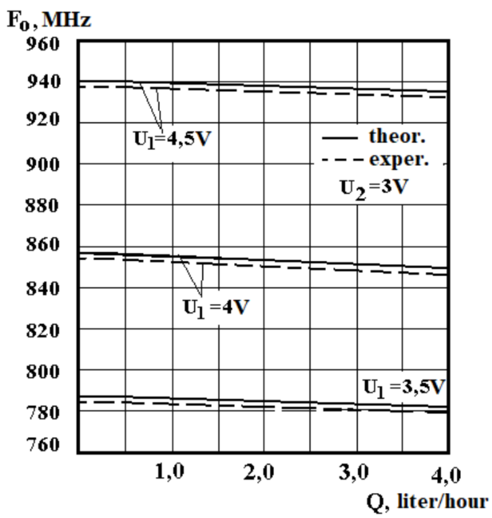


Fig. 6. Theoretical and experimental dependence of the generation frequency on gas flow

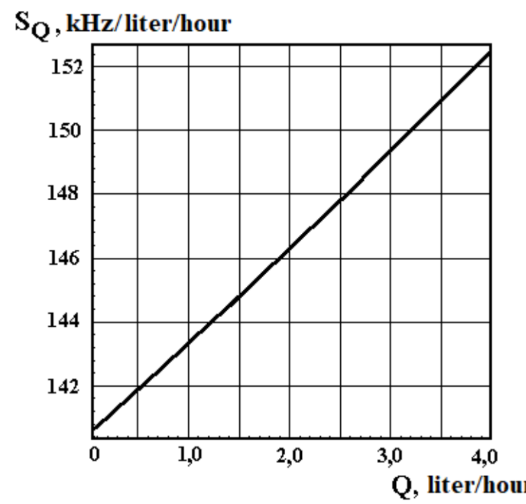


Fig. 7. The dependence of the sensitivity of the transducer on gas flow

The circuit of the optical-frequency gas flow transducer is manufactured using hybrid technology and consists of a BFT92 type bipolar transistor and a gallium arsenide transistor with a Schottky barrier type MGF1403. The photosensitive element was a PGM5516 photoresistor. External inductance made by spraying. Figure 6 shows the theoretical and experimental dependences of the transformation function, as can be seen from the graph, the discrepancy between the theoretical and experimental curves is satisfactory, which allows us to consider the theoretical calculations correct. The adequacy of the developed mathematical model is defined as a relative error, which is $\pm 1.5\%$. Figure 7 shows the dependence of the sensitivity of the transducer on the gas flow rate, it can be seen from the graph that the sensitivity of the developed optical-frequency gas flow transducer lies in the range from 142 kHz/liter/hour to 152 kHz/liter/hour.

Theoretical and experimental dependences of the generation frequency on the supply voltage are presented in Fig. 8. It was experimentally established that with an increase in gas flow from 0 liter/hour to 4 liter/hour, the generation frequency decreases from 857.3 MHz to 849.6 MHz. Studies have shown that by choosing a constant voltage supply mode, a linear dependence of the generation frequency on gas flow can be obtained. Figure 9 shows the experimental dependences of the generation frequency on the ambient temperature. The optimal supply voltage is 3.3 V, at which there is the smallest change in the generation frequency in the range from 20 °C to 80 °C.

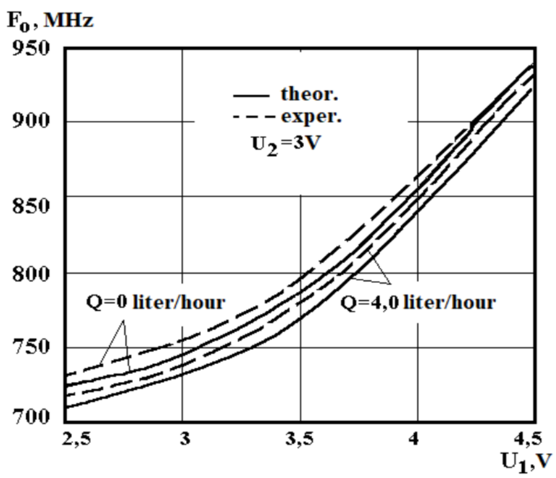


Fig. 8. Theoretical and experimental dependence of the generation frequency on the supply voltage

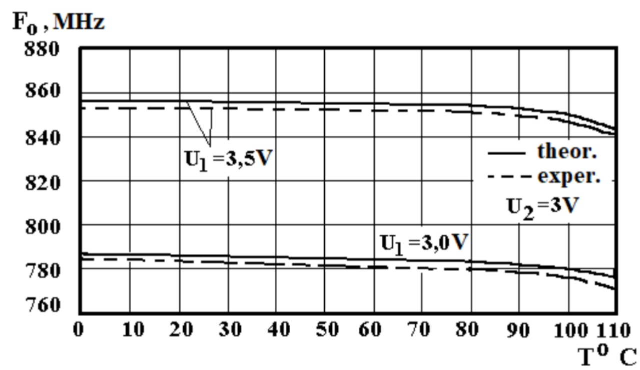


Fig. 9. Dependence of the frequency of generation on temperature

In the temperature range from 20°C to 50°C, the most temperature-stable operation of the transducer exists, while the sensitivity is 146 kHz/liter/hour (Fig. 7). A further increase in the sensitivity and expansion of the operating frequency range of the optical-frequency gas flow transducer is possible provided that photodiodes or phototransistors are used as photosensitive elements.

## 3. CONCLUSIONS

The schematic diagram and design of an optical-frequency gas flow transducer, which operates in the microwave range of 0.85-1.5 GHz, and consists of a bipolar and field-effect transistor with a Schottky barrier, is proposed as a photosensitive element. Theoretically and experimentally, the possibility of controlling both the reactive component of the impedance and the negative differential resistance from a change in the control voltage is shown, it extends the functionality of the optical transducers and allows linearization of the conversion function within (0.1 to 0.2)%. Experimental studies have shown that the greatest sensitivity and linearity of the conversion function of an optical-frequency gas flow transducer lies in the range from 3 V to 3.5 V. The sensitivity of the developed optical-frequency gas flow transducer based on a transistor structure with NDR is 146 kHz/liter/hour, and the measurement error is ± 1.5%.

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