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SECTION 4. ELECTRONICS

4.1 Frequency transducers of gas concentration for the diagnosis of strains of bacteria Helicobacter pylori

One of the directions of increasing the efficiency of diagnostics of various diseases using the latest methods and means, as well as a more complete and versatile analysis of signs, is an urgent area of modern medicine. The non-invasive method of analyzing the patient's exhaled air has recently attracted increased interest. To date, the definitions of various strains of bacteria Helicobacter pylori (H. pylori) acquired widespread importance due to its prevalence and great role in the development of many serious gastrointestinal diseases [157-159].

In medical practice, modern means of diagnosis of Helicobacter pylori infection are used and a new anti-infectious strategy for the treatment of gastroduodenal diseases is used [160]. Currently from methods of respiratory diagnostics H. pylori predominantly non-invasive C_{13}-urease breath test, which has a high diagnostic reliability. An alternative method of respiratory diagnostics is a method based on the determination of ammonia (NH_3) in the exhaled air by the alveoli and the concentration of ammonia coming from the stomach, when assessing the total concentration of ammonia [161].

A promising direction in the construction of gas concentration measuring transducers for respiratory diagnostics is the use of gas concentration frequency transducers based on the reactive properties of transistor structures with negative differential resistance (NDR) [162, 163]. This type of transducers allows solving the problem of using analog-to-digital transducers, since it implements the method of conversion "informative signal - frequency", which is one of the best for further processing on a computer [164]. Theoretical and experimental studies have shown that using the reactive properties of semiconductor devices and transistor structures in which there is a negative differential resistance, In the course of analyzing the optimal design of the gas concentration transducer, it was concluded that it is advisable to use the frequency method of converting information. This method makes it possible to increase the sensitivity of measuring the monitored parameter, in particular NH_3, in diagnostic medical systems, as well as to ensure high noise immunity of the informative signal.

In principle, self-oscillating transistor structures with negative differential resistance are a transistor analogue of the negatron. The I-V characteristic of such structures has a falling section, which corresponds to a negative differential resistance, which is provided by internal feedback and serves as a compensation for energy losses at the active resistances of the circuit. The complex resistance of such a structure, depending on the type of its current-voltage characteristic, has a capacitive or inductive character, and the value depends on the voltage applied to its input [168]. When such a structure is connected to an inductance, a resonant oscillatory circuit is formed. If the magnitude of the voltage drop and the magnitude of the complex resistance of the transistor structure depends on the magnitude of the measuring parameter,

In fig. 1 shows a schematic diagram of a metal-oxide (MOX) based gas concentration transmitter with a sensitive element to NH_3. The element GGS4430T from UST Umwelt Sensor Technik GmbH is used as a gas sensitive element. Finding the optimal operating power point for such a circuit is carried out using two constant voltage sources: supply voltage U_2 and control voltage U_1 (Fig. 1) [169].

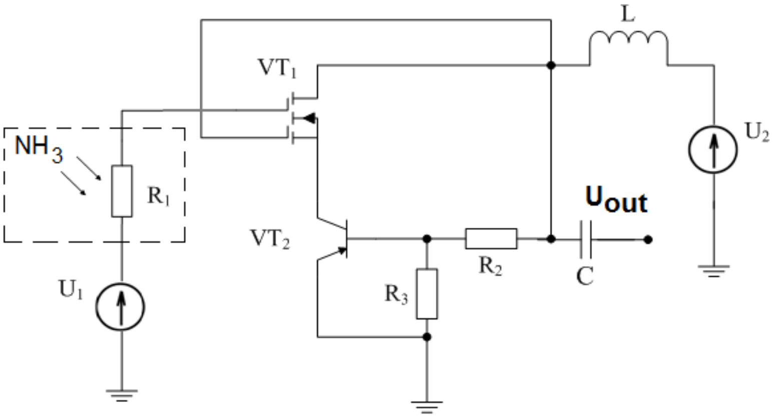
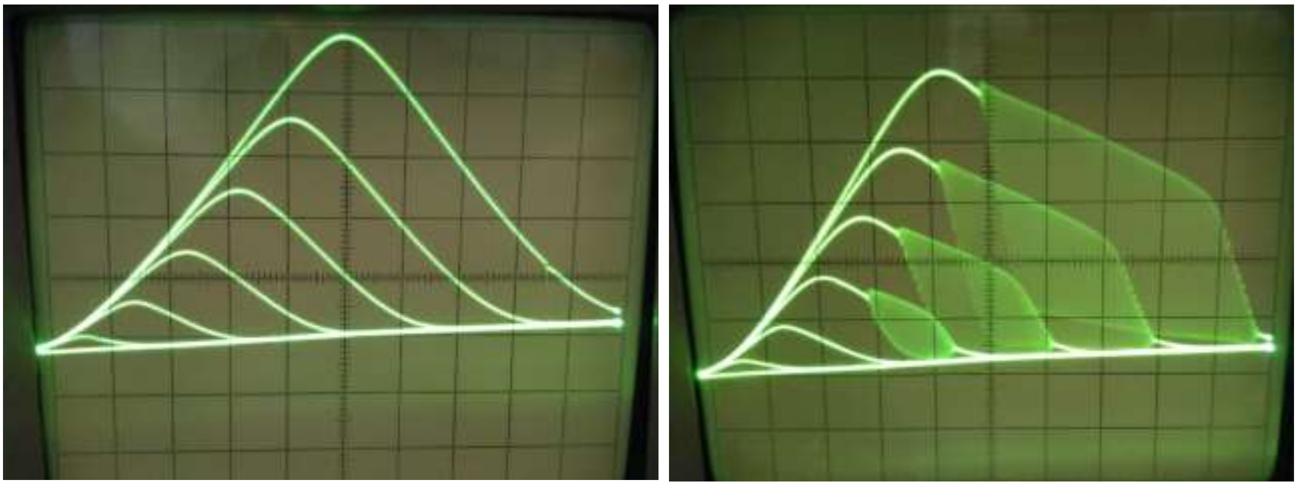


Figure 1. Frequency transducer of gas based on transistor structure with NDR for the diagnosis of strains of the bacteria Helicobacter Pylori.

When the gas concentration changes, the conductivity of the sensitive element, which adsorbs the NH_3 molecules, changes, which in turn changes the active and reactive components of the impedance of the transistor structure. The reactive component of the impedance of the transistor structure has a capacitive character.



a) b)

Figure 2. Static (a) and dynamic (b) I-V characteristic of a frequency transducer of gas concentration.

This capacitance is part of the total capacitance and arises at the drain electrodes of the two-gate MOS transistor and the collector of the bipolar transistor. This capacitance together with the inductance L form a resonant oscillatory circuit, which, taking into account the above, has a resonant oscillation frequency dependent on the gas concentration. Figure 2 shows a family of experimental static and dynamic volt-ampere characteristics of a gas concentration frequency transducer.

To create a mathematical model of a frequency transducer for gas concentration in Fig. 3 shows a nonlinear equivalent circuit of a frequency transducer.

On the nonlinear equivalent circuit of the frequency transducer of ammonia concentration, the elements are designated as follows: U_1, U_2 – power supplies; L – inductance; $R_1(C)$ – gas sensitive MOX element; R_4 – internal resistances of power supplies; R_2 and R_3 – load resistances of drain-source and base-collector transitions of field-effect and bipolar transistors; R_{ds}, R_d, R_s, R_e, R_c, R_b – volume resistances of the channel, drain, source of the field-effect transistor, emitter, collector and base of the bipolar transistor; C_e, C_c – capacitance of the emitter and collector junctions of the bipolar transistor; C_s, C_d, C_{ds} – capacitance gate-source, gate-drain, and capacitance of the field-effect transistor; I_f, I_r – forward and reverse current of the bipolar transistor; I_{dr}, I_{df} – currents of internal transitions base-collector and base-emitter of a bipolar transistor; I_{pt} – the channel current of the field-effect transistor.

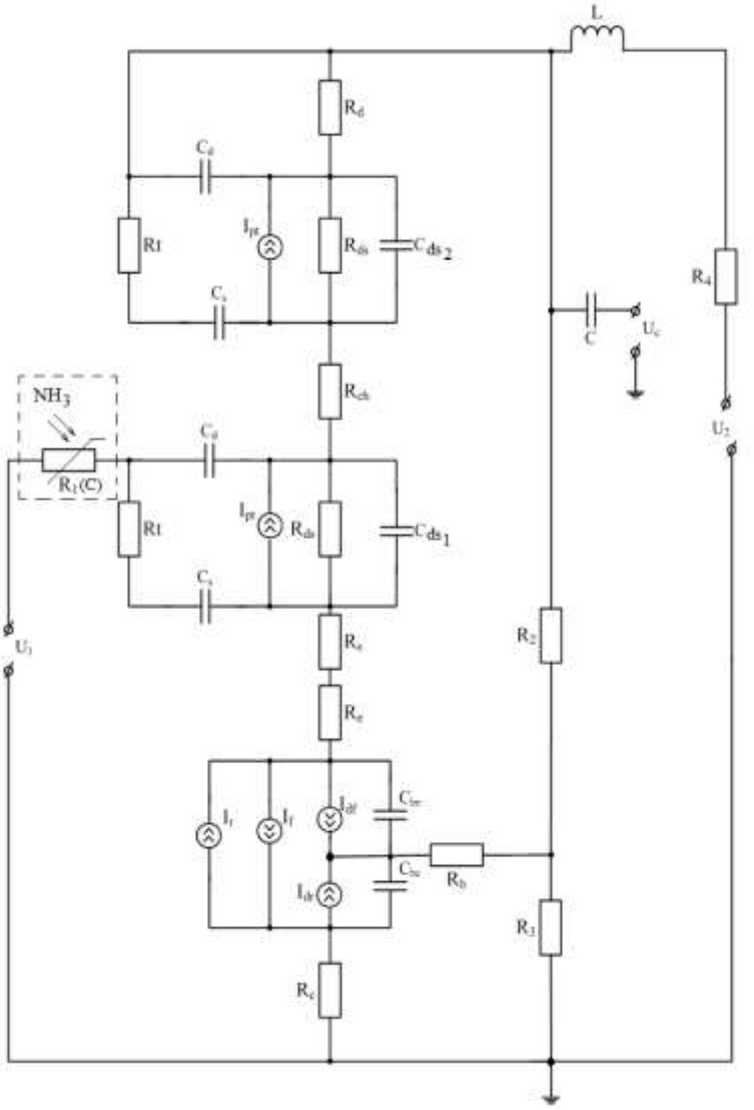


Figure 3. Equivalent circuit of a frequency transducer for ammonia concentration.

To construct a mathematical model of a frequency transducer of gas concentration, we use the state variable method, which allows us to determine the values of voltages and currents of circuit elements at each moment of time. According to the method of state variables, all capacities are presented in the form of independent voltage sources, and inductances in the form of current sources [170], and the following simplification is also made: $I_{bt} = (I_f - I_r)/QB$ where QB – coefficient of imperfection of bipolar transistor junctions. Having chosen the directions of bypassing the contours and designating the corresponding currents, we write the system of equations according to Kirchhoff's laws. We use the resulting system of equations to analyze the circuit using the state variable method.

$$\begin{cases} U_L = U_1 - (i_{R_2}(R_2 + R_{Cc}) + i_{R_3}R_3 - i_L R_4); \\ i_{R_3} = i_{R_2} - i_{R_b}; \\ i_{R_{ds}} = -U_{\mathrm{Cds}}/R_{ds}; \\ i_{c_d} = \left(U_{c_s} - U_{\mathrm{Cds}} - U_{c_d}\right)/R_t; \\ i_{R_d} = U_{\mathrm{Cds}}/R_d; \\ i_{R_2} = i_{C_d} + i_{R_d} + i_L; \\ i_{R_b} = \left(-U_{c_c} - i_{R_c}R_c - i_{R_3}R_3\right)/R_b; \\ i_{R_c} = \left(-R_1(C)(i_{c_d} + i_{c_s}) - i_{R_e}(R_e + R_s) - (U_2 + U_{c_s} + U_{c_c} + U_{c_e})\right)/R_c; \\ i_{R_1} = i_{c_d} + i_{c_s}; \\ i_{c_s} = -I_{pt} - i_{R_{ds}} + i_{c_{ds}} + i_{R_e}; \\ i_{c_{ds}} = i_{R_d} + I_{pt} - i_{c_d} + i_{R_{ds}}; \\ i_{c_c} = i_{R_c} + I_{bt} - I_{dr}; \\ i_{c_e} = i_{R_e} + I_{bt} + I_{df}; \\ i_{R_e} = i_{R_c} - i_{R_b}. \end{cases} \tag{1}$$

Assuming that the corresponding values of the voltages across the capacitors and the current through the inductance are given, we solve the system of equations (1) with respect to the following values: U_L, i_{c_d}, i_{c_s}, $i_{c_{ds}}$, i_{c_c}, i_{c_e}, by making these substitutions:

$$A_1 = \frac{-U_{\mathrm{Cds}} + U_{C_s} - U_{C_d}}{R_t} + I_{pt} + \frac{U_{C_d}}{R_d} - \frac{U_{\mathrm{Cds}}}{R_{ds}};\ A_2 = I_{bt} + I_{df};\ A_3 = U_2 + U_{C_s} + U_{C_c} + U_{C_e};\ A_4 = i_{C_d};$$

$$A_5 = -R_1(C)A_4 + I_{pt} - A_1 - \frac{U_{\mathrm{Cds}}}{R_{ds}} - A_3,\ A_6 = R_e + R_s + R_1(C);\ A_7 = 2U_{\mathrm{Cds}} + U_{C_e} + U_{C_d} + U_{C_c};$$

$$A_8 = \left(\frac{U_{C_s} - U_{\mathrm{Cds}} - U_{C_d}}{R_t} + \frac{U_{C_d}}{R_d} + i_L\right)(R_2 + R_3);\ A_9 = 1 - A_6 - \frac{A_6}{R_b}(2R_2 + R_3),$$

$$A_{10} = A_5 + A_6A_7 + A_6A_8 + \frac{A_6U_{C_c}(2R_2 + R_3)}{R_b};\ A_{11} = \frac{A_6(2R_2 + R_3)}{R_b}; A_{12} = \left(A_4 + \frac{U_{C_d}}{R_d}\right)(R_2 + R_3);$$

$$A_{13} = U_{C_c} A_9 + A_{10}\,;\; A_{14} = -A_7 A_9 - A_{10} + A_4 A_9 - \frac{U_{C_d}}{R_d} A_9\,;\; A_{15} = A_9 (2R_s + R_e)\,;\; A_{16} = A_{11} R_3 + A_9 R_3\,;$$

$$A_{17} = \frac{-U_{C_c} A_9 - A_{10} - 2A_{14} R_b - A_{15} R_b (I_{bt} + I_{pt}) + A_5 A_1 R_b + A_{15} R_b I_{dr} + \dfrac{A_{15} R_b U_{\mathrm{Cds}}}{R_{ds}}}{2A_{16} R_b + A_{11} R_3 + A_9 R_3}\,.$$

$$\begin{cases} i_{c_d} = A_4; \\ i_{c_c} = \dfrac{A_{10} + A_{11} R_3 A_{17}}{A_9 R_C}; \\ i_{c_e} = \dfrac{A_{14} + A_{16} A_{17}}{A_{15}} + I_{bt} - I_{dr}; \\ i_{c_s} = \dfrac{A_{14} + A_{16} A_{17}}{A_{15}} + I_{pt} - A_1 - \dfrac{U_{C_{ds}}}{R_{ds}}; \\ i_{c_{ds}} = A_1; \\ U_L = U_1 - (A_{12} + i_L (R_2 + R_3 + R_4)) + A_{17}. \end{cases} \tag{2}$$

Since the voltages and currents of the gas concentration frequency transducer circuit change over time, then, given that the capacitance current and voltage across the inductor are described by the expressions: $i_C = C\frac{dU_C}{dt}$, $U_L = L\frac{di_L}{dt}$. If we take into account that each instantaneous value of voltage and current in the equivalent circuit is a function of time, then we can write the left-hand sides of the equations in the form of first-order differential equations and rewrite system (2) in the form of a system of equations (3).

Considering that the system of equations (3) contains terms that describe nonlinear elements (current sources), the system is nonlinear. Non-linear circuit elements describe the currents of non-linear internal sources of circuit elements. The dynamic model of the autogenerating secondary transducer of gas concentration (3) makes it possible to determine the value of the output signal frequency depending on the change in gas concentration at any time.

$$\begin{cases} C_d \dfrac{dU_{C_d}(t)}{dt} = \dfrac{U_{C_s}(t) - U_{Cds}(t) - U_{C_d}(t)}{R_t}; \\ C_C \dfrac{dU_{C_C}(t)}{dt} = \dfrac{U_{C_e}(t) - U_{Cds}(t) - U_{C_d}(t)}{R_t} + I_{bt} - I_{dr}; \\ C_e \dfrac{dU_{C_e}(t)}{dt} = A_1 + I_{bt} - I_{dr}; \\ C_s \dfrac{dU_{C_s}(t)}{dt} = -I_{pt} - \dfrac{U_{Cds}(t)}{R_{ds}} + A_3; \\ L \dfrac{di_L(t)}{dt} = U_2 - i_L(t) \cdot R_4 - \dfrac{U_{C_e}(t) + U_{C_C}(t) + U_{C_s}(t)}{R_e + R_s}; \\ C_{eqv}(t) \dfrac{dU_{Cds}(t)}{dt} = \dfrac{U_{C_d}(t)}{R_d} + I_{pt} - \dfrac{U_{C_s}(t) - U_{Cds}(t) - U_{C_d}(t)}{R_t} + \dfrac{U_{Cds}(t)}{R_{ds}}. \end{cases} \tag{3}$$

The verification of the developed mathematical model, carried out in the Maple 13 environment [171], makes it possible to verify its adequacy. The calculation shows that in the presence of a certain level of gas concentration, sinusoidal oscillations appear at the output of the circuit and their frequency depends on the level of gas concentration (NH_3). So, in fig. 4 shows the graphs of oscillations at the output of the frequency transducer at three values of the gas concentration (NH_3).

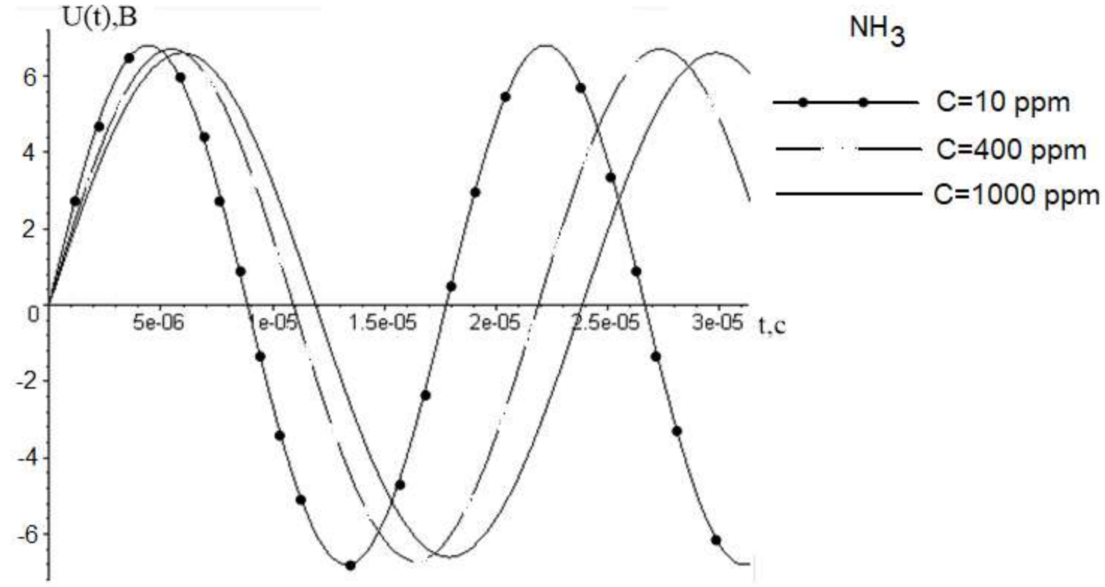


Figure 4. Change in the output signal of the frequency transducer from changes in the concentration of ammonia.

To conduct an experimental verification of the mathematical model (system of equations (3)), a hybrid integrated circuit was developed based on a two-gate MOS transistor BF998 and a bipolar transistor BC857.

In order to obtain the dependence of the output parameter of the frequency transducer of gas concentration on the value of the measured parameter, as well as for adequate calibration of the device, a conversion function is used. Based on the Lyapunov stability conditions [172], based on the resonance condition of the oscillatory circuit, the frequency of the output signal frequency transducer of gas concentration will be determined by the following expression:

$$F_0 = \frac{1}{2\pi}\sqrt{\frac{B_1 + \sqrt{B_1^2 + 4L_1C_{GD}(C_{CE}R_1(C)R_4)^2}}{2L_1C_{GD}(R_1(C)R_4C_{CE})^2}}\,, \tag{4}$$

where $B_1 = L_1C_{GD} - (C_{CE}R_1(C)R_4)^2 - C_{GD}C_{CE}R_1^2(C)R_4^2$, L – external inductance, C_{CE} – the throughput capacity of the collector-emitter of the bipolar transistor VT2, C_{GD} – the gate-drain capacitance of the field-effect transistor VT1.

Taking the derivative of the conversion function with respect to the gas concentration, we obtain a sensitivity equation for a given measuring transducer, which is analytically described by the following formula:

$$\begin{aligned}
&S_C^{F_0} = 0.0562\Bigg(\frac{1}{B_2}\Bigg(2C_{ce}^2R_1(C)R_4^2\left(\frac{\partial R_1(C)}{\partial C}\right) - 2C_{ce}^2R_1^2(C)R_4 - 2C_{gd}C_{ce}R_1(C)R_4^2\left(\frac{\partial R_1(C)}{\partial C}\right) - 2C_{gd}C_{ce}R_1^2(C)R_4 + \\
&+\frac{1}{2}\Bigg(-2C_{ce}^2R_1(C)R_4^2\left(\frac{\partial R_1(C)}{\partial C}\right) - 2C_{ce}^2R_1^2(C)R_4 - 2C_{gd}C_{ce}R_1(C)R_4^2\left(\frac{\partial R_1(C)}{\partial C}\right) - 2C_{gd}C_{ce}R_1^2(C)R_4 + \\
&+8L_1C_{gd}C_{ce}^2R_1(C)R_4^2\times\left(\frac{\partial R_1(C)}{\partial C}\right) + 8L_1C_{gd}C_{ce}^2R_1^2(C)R_4\Bigg)\Big/B_3\Big) - \frac{1}{B_2}\Big(2\Big(L_1C_{gd} - C_{ce}^2R_1^2(C)R_4^2 - \\
&-C_{gd}C_{ce}R_1^2(C)R_4^2 + B_3\left(\frac{\partial R_1(C)}{\partial C}\right)\Big)\Big) - \frac{1}{B_2}\Big(2\Big(L_1C_{gd} - C_{ce}^2R_1^2(C)R_4^2 - C_{gd}C_{ce}R_1^2(C)R_4^2 + B_3 -\Big)\Big)\Big)\Big)\Big/ \\
&\left(\frac{1}{B_2}\Big(L_1C_{gd} - C_{ce}^2R_1^2(C)R_4^2 - C_{gd}C_{ce}R_1^2(C)R_4^2 + B_3\Big)\quad\right)^{1/2},
\end{aligned} \tag{5}$$

where $B_2 = 2L_1C_{GD}(R_1(C)R_4C_{CE})^2, B_3 = \sqrt{B_1 + 4L_1C_{GD}(C_{CE}R_1(C)R_4)^2}$.

Based on expression (4), graphs of the dependence of the generation frequency of the autogenerating transducer depending on the value of the gas concentration were obtained (Fig. 5).

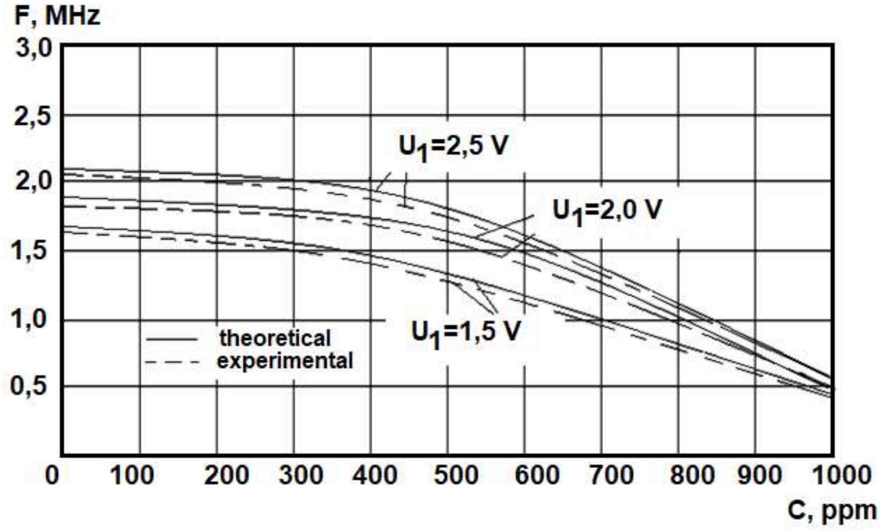


Figure 5. Dependence of the generation frequency on the change in NH_3 concentration at different values of the control voltage.

Fig. 5 it can be seen that with an increase in the control voltage, the frequency of generation of the frequency transducer of gas concentration increases in all ranges of measurement of the concentration of ammonia. On the basis of the obtained analytical expression (5), the dependence of the sensitivity of the gas concentration transducer was calculated over the entire range of the measured parameter (Fig. 6).

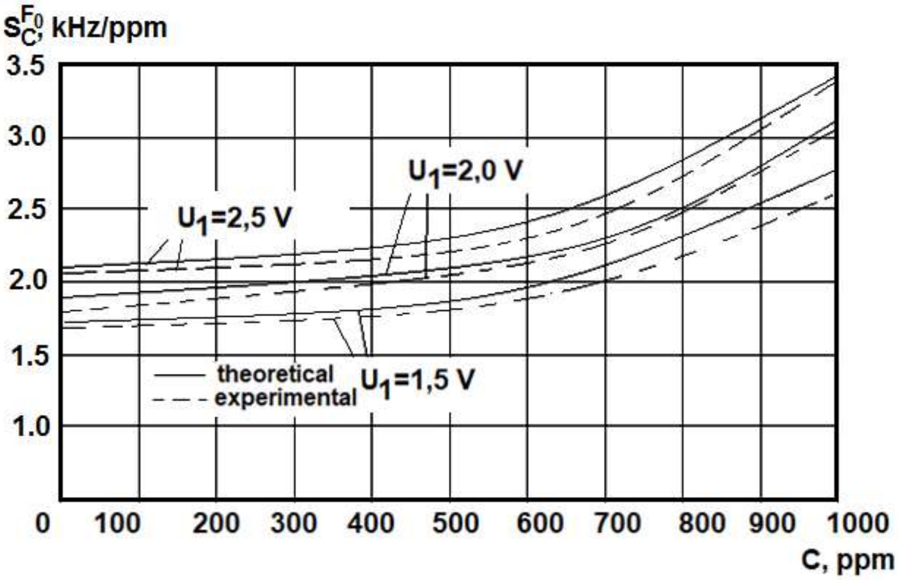


Figure 6. Dependence of the frequency transducer sensitivity at different values of the control voltage.

Fig. 5 that the frequency decreases proportionally with an increase in the ammonia concentration, so the frequency takes values from 2.12 MHz to 0.53 MHz when the HN_3 concentration changes from 0 to 1000 ppm. The sensitivity of the developed frequency transducer for gas concentration ranges from 2.1 kHz/ppm to 3.4 kHz/ppm. The adequacy of the developed model in comparison with the experiment is determined in the form of a relative error and does not exceed ± 2.5%.

To create a gas concentration transducer, a circuit solution using an active inductive element is proposed in a completely integrated form. The circuit of a microelectronic gas concentration transducer with a frequency output and active inductance is shown in Fig. 7 [173]. The proposed microelectronic gas concentration transducer circuit is built on a transistor structure of three bipolar transistors on one HFA3046 crystal. At the electrodes, the collector-emitter of the bipolar transistor VT3 and the base-emitter of the bipolar transistor VT2, the current-voltage characteristic has a falling section, which corresponds to the appearance of a negative differential resistance. The operating point of the DC generator is selected on the falling section of the current-voltage characteristic. Oscillatory system of the oscillator (Fig. 7) consists of a capacitance that exists on the collector-emitter electrodes of the bipolar transistor VT3, as well as an active inductance based on the bipolar transistor VT4 and phase-shifting circuit C1R4. Resistors R1-R3 provide the mode of operation of bipolar transistors VT1-VT4 for direct current.

Microelectronic gas concentration transducer works as follows. By choosing a constant voltage source U1, we achieve the generation of electrical oscillations of the auto-generator. At the next action of ammonia NH3 on the gas-sensitive resistive element R2 based on the MEMS sensor MiCS-6814, which changes its resistance, leads to a change in the equivalent capacitance of the oscillatory circuit of the oscillator, and this, in turn, changes the generation frequency.

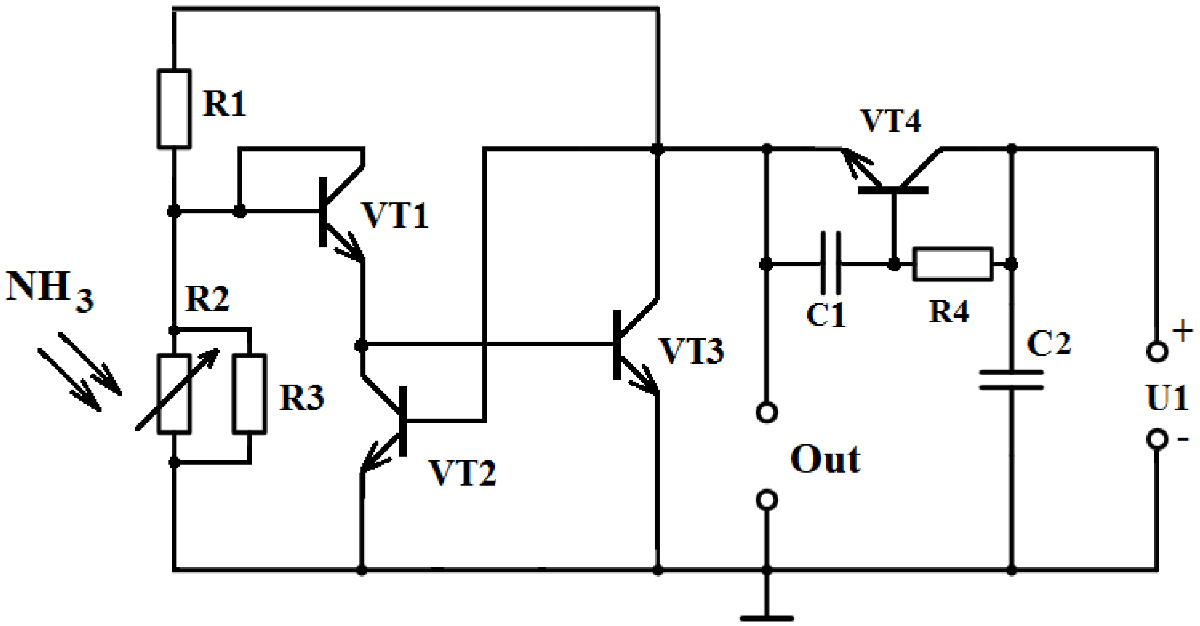


Figure 7. Electrical diagram of a gas transducer with a frequency output.

The conversion function and sensitivity of the frequency microelectronic gas concentration transducer are determined based on the equivalent circuit of the device. The resonant frequency, which is dependent on the change in gas concentration, is a conversion function of the sensor. It is determined on the basis of equality to zero of the reactive component of the total input impedance and has the form

$$F(C)=\frac{1}{2\pi R_g C(C)}\left[\frac{R_g^2 C(C)}{L}-1\right]^{1/2}. \qquad (6)$$

The sensitivity of a frequency microelectronic gas concentration transducer is determined based on expression (6) and is described by the equation

$$S_C^{F_p}=-\frac{1}{2}\frac{\sqrt{\frac{R_g^2 C(C)}{L}-1}\left(\frac{dC(C)}{dC}\right)}{\pi R_g^2 C(C)}+\frac{1}{2}\frac{\frac{dC(C)}{dC}}{\pi L\sqrt{\frac{R_g^2 C(C)}{L}-1}}. \qquad (7)$$

In fig. 8 shows the dependence of the conversion function, that is, the dependence of the resonant frequency on the gas concentration (NH_3). As you can see from the graph, the conversion function is non-linear.

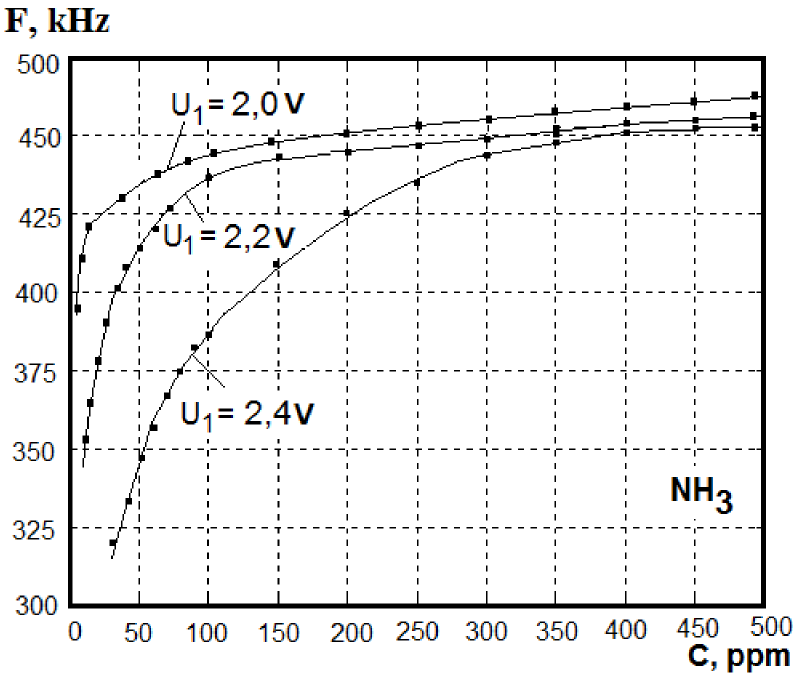


Figure 8. Dependence of vibration frequency on changes in ammonia concentration.

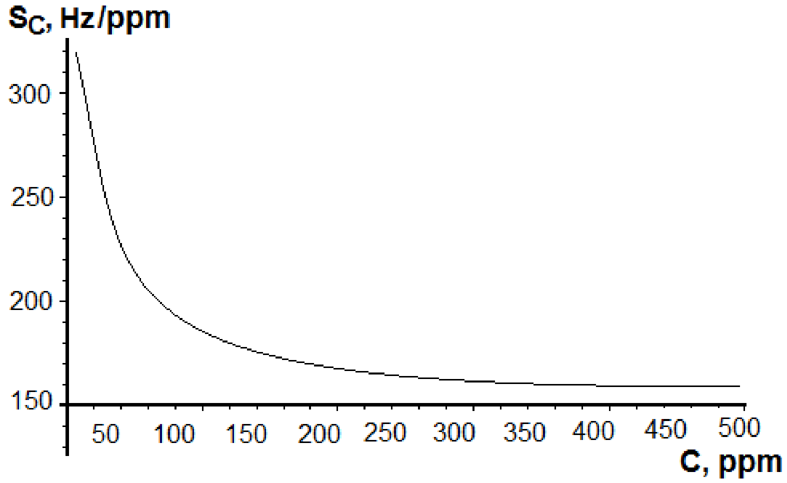


Figure 9. Dependence of sensitivity on changes in ammonia concentration.

In fig. 9 shows the dependence of the sensitivity of the frequency microelectronic transducer of gas concentration. Analysis of the graph shows that the highest sensitivity of the device lies in the range from 5 ppm to 75 ppm and ranges from 325 Hz/ppm to 225 Hz/ppm, and in the range from 150 ppm to 500 ppm it is 165 Hz/ppm, the lowest sensitivity value is 161 Hz/ppm from 300 ppm to 500 ppm.

Consider another schematic solution for creating a gas concentration transducer. In fig. 10 shows a diagram of an optical-frequency transducer of gas concentration with sensitive elements to optical radiation based on MOS field-effect transistors with an active inductive element [174].

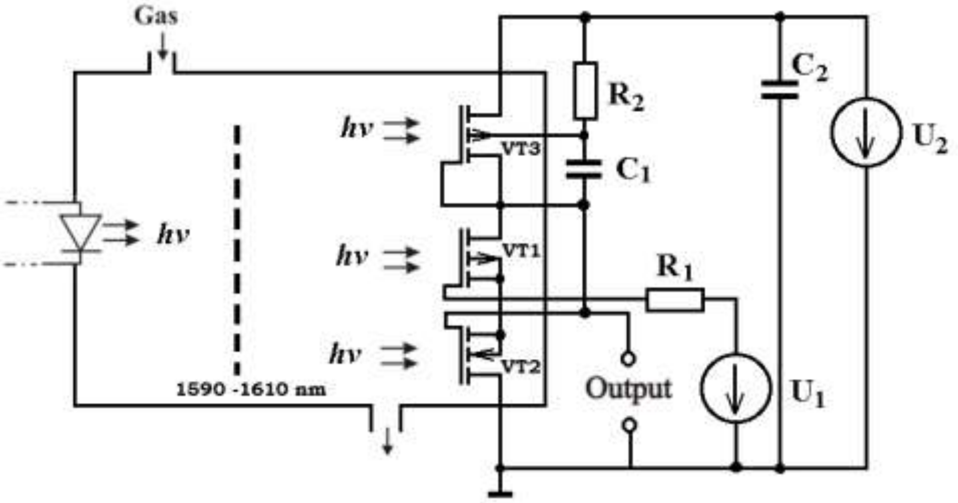


Figure 10. Diagram of an optical-frequency gas transducer.

Figure 10 shows a diagram of an optical-frequency transducer device, in which the capacitance of the oscillatory circuit of the oscillator is realized by the capacitive component of the impedance at the drain-drain electrodes of the field photosensitive transistors VT1 and VT2, and the inductance is realized by the inductive component of the impedance at the source-drain electrodes of the photosensitive transistor VT3. The absorption spectrum of NH_3 is in the infrared range of 1590 - 1610 nm [175].

Field-effect phototransistors with a metal-oxide-semiconductor (MOS) structure have found wide application in systems for receiving and processing optical information [176]. At present, a theory of the photoreactive effect in MOS transistors has been developed, which quite accurately describes the static characteristics of such devices [177]. However, in the dynamic mode, when a small alternating signal and optical radiation act on the channel, the theoretical issues of changing the parameters of the transistor have not been fully studied. On the other hand, the dependence of the parameters of field-effect phototransistors on optical radiation in a dynamic mode makes it possible to create optical-frequency transducers with optical frequency tuning, which in their characteristics are much better than analog devices [169]. The use of field-effect transistor structures with negative resistance makes it possible to realize a frequency transducer, in which both capacitance and inductance based on field-effect transistors depend on optical radiation, which significantly improves the sensitivity and accuracy of the transducer. On the basis of a nonlinear equivalent circuit, the parameters of the optical-frequency gas transducer are calculated. During the calculation of the impedance, the parameter values of the BSS84P and BSS7728 transistors were used. The complete model of the photoreactive MOS transistor takes into account the influence of small-signal parameters of the active zone of the crystal, photodiode structures of the source and drain, as well as parasitic parameters of the case.

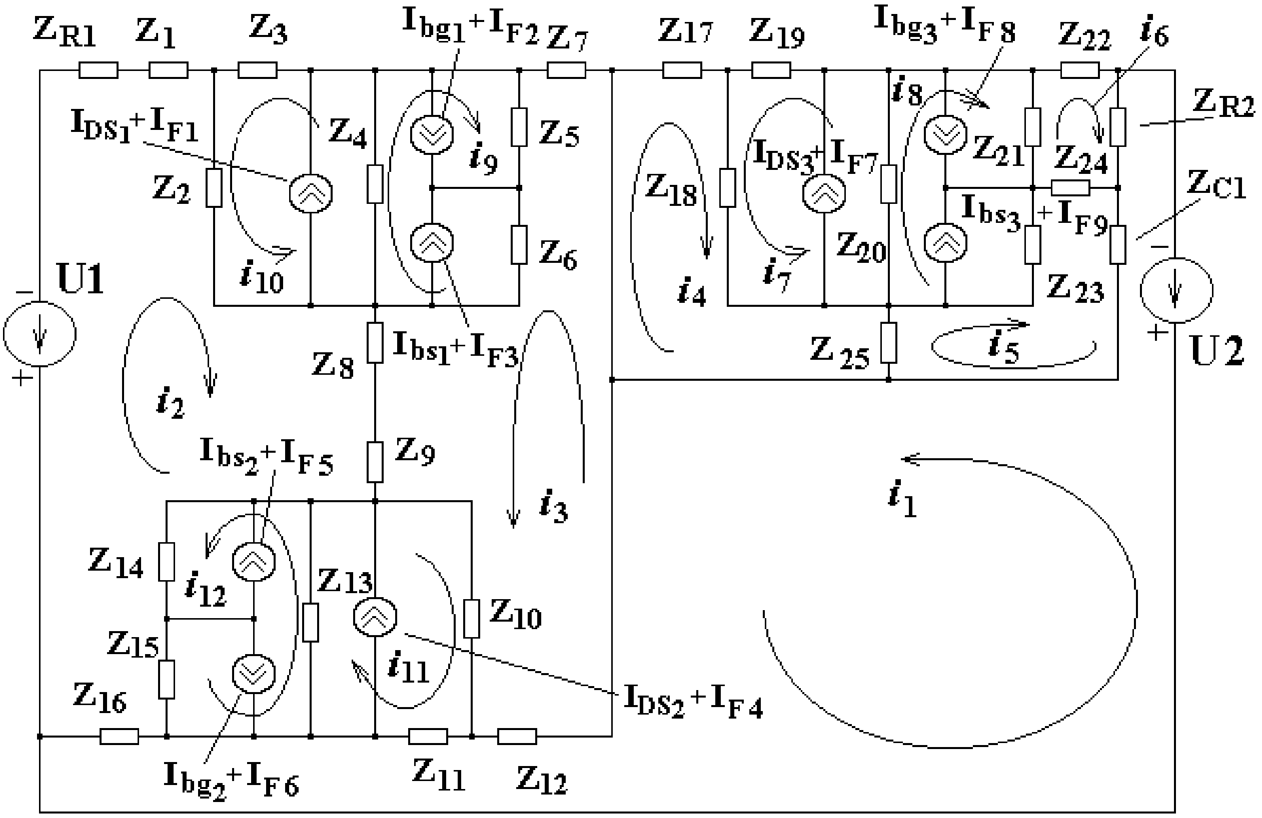


Figure 11. Equivalent circuit of an optical-frequency gas transducer.

The Kirchhoff system of equations has the form

$$
\begin{cases}
U_2 = (Z_{R2} + Z_{C1} + Z_{12} + Z_{11} + Z_{16})i_1 + Z_{R2}i_6 + Z_{C1}i_5 - Z_{12}i_3 + Z_{11}i_{11} + Z_1(I_{DS2} + I_{F4}) + Z_{16}i_2, \\
U_1 = (Z_{R1} + Z_1 + Z_2 + Z_8 + Z_9 + Z_{14} + Z_{15} + Z_{16})i_2 + Z_2(i_{10} + I_{DS1} + I_{F1}) + Z_8 i_3 + Z_9 i_3 + Z_{14}i_{12} + Z_{14}(I_{bs2} + I_{F5} + I_{DS2} + I_{F4}) - \\
-Z_{14}(I_{bg2} + I_{F6}) + Z_{15}(i_{12} + I_{bs2} + I_{F5} - I_{bg2} - I_{F6} + I_{DS2} + I_{F4}) + Z_{16}i_1, \\
0 = (Z_7 + Z_5 + Z_6 + Z_8 + Z_9 + Z_{10} + Z_{12})i_3 + Z_5 i_9 - Z_5(I_{bg1} + I_{F2}) + Z_5(I_{bs1} + I_{F3} + I_{DS1} + I_{F1}) + Z_6(I_{bs1} + I_{F3} - I_{bg1} - \\
-I_{F2} + I_{DS1} + I_{F1}) + Z_8 i_2 + Z_9 i_2 + Z_{10}(i_{11} + I_{DS2} + I_{F4} + I_{bs2} + I_{F5} - I_{bg2} - I_{F6}) - Z_{12}i_1, \\
0 = (Z_{17} + Z_{18} + Z_{25})i_4 + Z_{18}i_7 + Z_{18}(I_{DS3} + I_{F7}) + Z_{18}(I_{bs3} + I_{F9}) - Z_{18}(I_{bg3} + I_{F8}) - Z_{25}i_5, \\
0 = (Z_{24} + Z_{C1} + Z_{25} + Z_{23})i_5 - Z_{24}i_6 + Z_{C1}i_1 - Z_{25}i_4 + Z_{23}(-I_{DS3} - I_{F7} - I_{bs3} - I_{F9} + I_{bg3} + I_{F8} - i_8), \\
0 = (Z_{22} + Z_{R2} + Z_{24} + Z_{21})i_6 + Z_{R2}i_1 - Z_{24}i_5 - Z_{21}i_8 + Z_{21}(I_{bg3} + I_{F8} - I_{bs3} - I_{F9} - I_{DS3} - I_{F7}), \\
0 = (Z_{18} + Z_{20} + Z_{19})i_7 + Z_{18}i_4 + Z_{18}(I_{DS3} + I_{F7} - I_{bg3} - I_{F8} + I_{bs3} + I_{F9}) + Z_{20}i_8 - Z_{20}(I_{DS3} + I_{F7}) + Z_{20}(I_{bg3} + I_{F7}) - \\
-Z_{20}(I_{bs3} + I_{F9}) + Z_{19}(I_{DS3} + I_{F7}) - Z_{19}(I_{bg3} + I_{F8}) + Z_{19}(I_{bs3} + I_{F9}), \\
0 = (Z_{21} + Z_{23} + Z_{20})i_8 - Z_{21}i_6 - Z_{21}(I_{bg3} + I_{F8}) + Z_{21}(I_{bs3} + I_{F9}) + Z_{21}(I_{DS3} + I_{F7}) - Z_{23}i_5 + Z_{23}(I_{bs3} + I_{F9}) - Z_{23}(I_{bg3} + \\
+I_{F8}) + Z_{23}(I_{DS3} + I_{F7}) + Z_{20}i_7 - Z_{20}(I_{DS3} + I_{F7}) - Z_{20}(I_{bs3} + I_{F9}) + Z_{20}(I_{bg3} + I_{F8}), \\
0 = (Z_4 + Z_5 + Z_6)i_9 - Z_4(I_{DS1} + I_{F1}) - Z_4(I_{bs1} + I_{F3}) + Z_4(I_{bg1} + I_{F1}) + Z_4 i_{10} + Z_5 i_3 - Z_5(I_{bg1} + I_{F2}) + \\
+Z_5(I_{bs1} + I_{F3}) + Z_5(I_{DS1} + I_{F1}) + Z_6 i_3 + Z_6(I_{DS1} + I_{F1}) + Z_6(I_{bs1} + I_{F3}) - Z_6(I_{bg1} - I_{F2}), \\
0 = (Z_2 + Z_4 + Z_3)i_{10} + Z_2 i_2 + Z_2(I_{bs1} + I_{F3}) - Z_2(I_{bg1} + I_{F2}) + Z_2(I_{DS1} + I_{F1}) + Z_4 i_9 - Z_4(I_{DS1} + I_{F1}) - \\
-Z_4(I_{bs1} + I_{F3}) + Z_4(I_{bg1} + I_{F2}) + Z_3(I_{DS1} + I_{F1}) + Z_3(I_{bs1} + I_{F3}) - Z_3(I_{bg1} + I_{F2}), \\
0 = (Z_{10} + Z_{11} + Z_{13})i_{11} + Z_{10}(i_3 + I_{DS2} + I_{F4} + I_{bs2} + I_{F5} - I_{bg2} - I_{F6}) + Z_{11}i_1 + Z_{13}i_{12} + Z_{11}(I_{DS2} + I_{F4} + I_{bs2} + I_{F5} - \\
-I_{bg2} - I_{F6}) + Z_{13}(-I_{bs2} - I_{F5} + I_{bg2} + I_{F6} - I_{DS2} - I_{F4}), \\
0 = (Z_{13} + Z_{14} + Z_{15})i_{12} + Z_{13}(i_{11} - I_{DS2} - I_{F4} - I_{bs2} - I_{F5} + I_{bg2} + I_{F6}) + Z_{14}(i_2 + I_{bs2} + I_{F5} - I_{bg2} - I_{F6} + I_{DS2} + I_{F4}) + \\
+Z_{15}(i_2 + I_{bs2} + I_{F5} - I_{bg2} - I_{F6} + I_{DS2} + I_{F4}).
\end{cases}
\tag{8}
$$

where $Z_{R1} = R1$, $Z_1 = R_{G1}$, $Z_3 = -j/(\omega C_{GD1})$, $Z_4 = Z_K$, $Z_5 = -j/(\omega C_{BD1})$, $Z_7 = R_{D1}$,

$Z_8 = R_{S1} + j\omega L_{S1}$, $Z_2 = \dfrac{R_{GS1}}{1+\omega^2 R_{GS1}^2 C_{GS1}^2} - j\dfrac{R_{GS1}^2 \omega C_{GS1}}{1+\omega^2 R_{GS1}^2 C_{GS1}^2}$, $Z_6 = \dfrac{R_{B1}}{1+\omega^2 R_{B1}^2 C_{BS1}^2} - j\dfrac{R_{B1}^2 \omega C_{BS1}}{1+\omega^2 R_{B1}^2 C_{BS1}^2}$,

$Z_{12} = R_{G2}$, $Z_{11} = -j/(\omega C_{GD2})$, $Z_{13} = Z_K$, $Z_{15} = -j/(\omega C_{BD2})$, $Z_{16} = R_{D2}$, $Z_9 = R_{S2} + j\omega L_{S2}$,

$Z_{10} = \dfrac{R_{GS2}}{1+\omega^2 R_{GS2}^2 C_{GS2}^2} - j\dfrac{R_{GS2}^2 \omega C_{GS2}}{1+\omega^2 R_{GS2}^2 C_{GS2}^2}$, $Z_{R2} = R2$, $Z_{14} = \dfrac{R_{B2}}{1+\omega^2 R_{B2}^2 C_{BS2}^2} - j\dfrac{R_{B2}^2 \omega C_{BS2}}{1+\omega^2 R_{B2}^2 C_{BS2}^2}$,

$Z_{17} = R_{G3}$, $Z_{19} = -j/(\omega C_{GD3})$, $Z_{20} = Z_K$, $Z_{21} = -j/(\omega C_{BD3})$, $Z_{22} = R_{D3}$, $Z_{25} = R_{S3} + j\omega L_{S3}$,

$Z_{18} = \dfrac{R_{GS3}}{1+\omega^2 R_{GS3}^2 C_{GS3}^2} - j\dfrac{R_{GS3}^2 \omega C_{GS3}}{1+\omega^2 R_{GS3}^2 C_{GS3}^2}$, $Z_{23} = \dfrac{R_{B3}}{1+\omega^2 R_{B3}^2 C_{BS3}^2} - j\dfrac{R_{B3}^2 \omega C_{BS3}}{1+\omega^2 R_{B3}^2 C_{BS3}^2}$, $Z_{C1} = -j/(\omega C_{C1})$.

The solution of the system of equations (8) was obtained by a numerical method on a personal computer in the "Matlab 9.3" computing environment. In general, the transformation function is described by the equation

$$\omega_0 = \left[L_{eq}(P) C_{eq}(P) \right]^{1/2}, \tag{9}$$

where ω_0 – circular frequency of generation, $L_{eq}(P)$ – the equivalent inductance of the oscillating circuit of the oscillator, $C_{eq}(P)$ – the equivalent capacity of the oscillating circuit of the oscillator, which is determined based on the solution of the system of equations (8). The sensitivity of the optical-frequency gas transducer is determined based on the equation (9)

$$\frac{d\omega_0}{dP} = -\frac{1}{2}\left[L_{eq}(P)C_{eq}(P)\right]^{-3/2}\left[C_{eq}(P)\frac{dL_{eq}(P)}{dP} + L_{eq}(P)\frac{dC_{eq}(P)}{dP}\right]. \tag{10}$$

To check theoretical calculations of the total resistance of MOS - transistors from the power of optical radiation, they were compared with experimental data. Experimental studies were carried out in the range of 1…1250 MHz using a complex transmission coefficient meter P4-37. The source of optical radiation was a light-emitting diode based on InGaAsP XL3528IRC/1500 s the maximum of the spectral distribution at the wavelength $\lambda = 1550$ nm. The radiation power was controlled using an OM3-65 device.

In fig. 12 shows the theoretical and experimental dependences of the generation frequency on the power of optical radiation. The frequency was measured using an AT-F2700 frequency meter. A decrease in the generation frequency is associated with an increase in the equivalent capacitance of the oscillatory circuit of the oscillator, which is caused by the photogeneration of nonequilibrium charge carriers in the channel regions, the source and drain p-n junctions of MOS transistors.

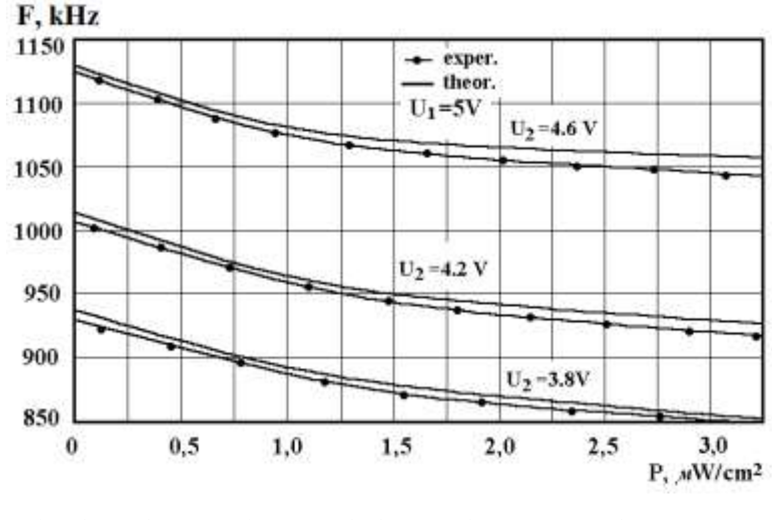


Figure 12. Theoretical and experimental dependences of the generation frequency on the power of optical radiation.

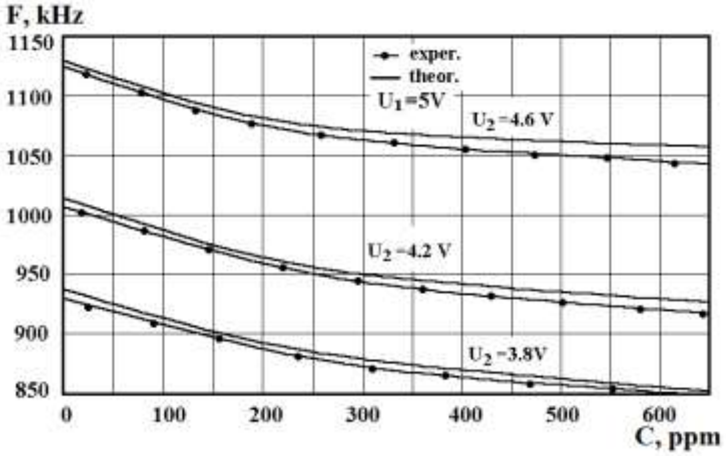


Figure 13. Theoretical and experimental dependences of the generation frequency on the NH_3 concentration.

The above considered mathematical model of an optical-frequency transducer of gas concentration for diagnosing strains of the bacterium Helicobacter pylori takes into account the effect of optical radiation on the channel, source and drain p-n junctions of MOS transistors. Photosensitive field-effect transistors implement the capacitance and inductance of the oscillatory circuit of an optical-frequency gas transducer, which change under the action of optical radiation, and, accordingly, the gas concentration, which made it possible to increase the sensitivity of the gas concentration transducer.

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