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PARAMETRIC AUTOGENERATOR TRANSDUCERS FOR MEASURING THE THICKNESS OF MATERIALS BASED ON CAPACITOR SENSITIVE ELEMENTS

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Анотація. У статті розглянуто основні характеристики параметричних автогенераторних товщиномірних перетворювачів з частотним вихідним сигналом. Конструкція запропонованих автогенераторних перетворювачів виконана на основі транзисторних структур з негативним диференціальним опором. В якості параметричних перетворювачів для вимірювання товщини матеріалів використовуються конденсатори з круглою і прямокутною кришками, які є пасивними елементами перетворювачів автогенераторів, що значно спрощує конструкцію приладів для вимірювання товщини матеріалів. Розроблено математичні моделі автогенераторних перетворювачів на основі принципу перетворення енергії постійного електричного поля в енергію змінного електричного поля, що дозволило отримати функції перетворення та чутливості автогенераторних перетворювачів без використання досить складного методу отримання рівнянь Кірхгофа з нелінійних еквівалентних схем параметричних перетворювачів. Показано, що основний внесок у зміну функцій перетворення та рівняння чутливості вносить зміна товщини вимірюваного матеріалу, яка викликає зміну еквівалентної ємності та від’ємного диференціального опору в коливальній системі автогенераторів, який змінює вихідну частоту перетворювачів автогенератора. Чутливість товщиномірних перетворювачів змінюється від 5,31 кГц/мкм до 7,5 кГц/мкм в діапазоні товщин від 0 до 500 мкм. Автогенераторні перетворювачі товщини з частотним виходом не потребують аналого-цифрових перетворювачів і підсилювачів для подальшої обробки інформаційних сигналів, що значно здешевлює інформаційно-вимірювальну апаратуру, а при роботі на надвисоких частотах можлива передача інформації. на значні відстані.

Ключові слова: перетворювач, частота, автогенератор, товщиномір, вимірювальний конденсатор, негативний диференціальний опір.

Abstract. The article examines the main characteristics of parametric autogenerator thickness measurement transducers with a frequency output signal. The design of the proposed autogenerator transducers is based on transistor structures with negative differential resistance. Capacitors with round and rectangular covers are used as parametric transducers for measuring the thickness of materials, which are passive elements of autogenerator transducers, which greatly simplifies the design of devices for measuring the thickness of materials. Mathematical models of autogenerator transducers were developed based on the principle of converting the energy of a constant electric field into the energy of an alternating electric field, which made it possible to obtain the conversion and sensitivity functions of autogenerator transducers without using a rather complicated method of obtaining Kirchhoff equations from nonlinear equivalent circuits of parametric transducers.

It is shown that the main contribution to the change in the conversion functions and the sensitivity equation is made by the change in the thickness of the measured material, which causes a change in the equivalent capacitance and negative differential resistance in the oscillating system of autogenerators, which changes the output frequency of the autogenerator transducers. The sensitivity of thickness measurement transducers varies from 5.31 kHz/μm to 7.5 kHz/μm in the thickness range from 0 to 500 μm. Autogenerator transducers for thickness measurement with frequency output do not require analog-digital transducers and amplifiers for further processing of informative signals, which significantly reduces the cost of information-measuring equipment, and when working at ultra-high frequencies, it is possible to transmit information over considerable distances.
Keywords: transducer, frequency, autogenerator, thickness measurement, measuring capacitor, negative differential resistance.

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INTRODUCTION

The modern stage of science and technology requires further development of accurate and instrumental instrumentation for various systems of direct and indirect measurement, conversion, coding, transmission and protection of metrological information. The use of new physical phenomena and principles of implementation allows the development of instruments for measuring thickness for various industries, such as the chemical industry, microelectronics and nanoelectronics technology [1, 2, 3, 4, 5].

Currently, there are various types of transducers for determining the thickness of materials used both in science and in production. However, most of them have low resolution, high sensitivity threshold and significant errors when measuring small material thicknesses [6, 7].

Devices created specifically for determining small and ultra-small sizes of films, such as radiation, X-ray, although they have high metrological parameters, are complex and dangerous for the health of the person who works with them [8, 9].

It is possible to eliminate the above-mentioned shortcomings on the basis of microelectronics autogenerator transducers operating in the "thickness-frequency" conversion mode, which significantly improves their metrological performance [10, 11].

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

One of the promising directions in the creation of transducers for determining the thickness is research based on the reactive properties of transistor structures with negative differential resistance, which allows creating devices with a frequency output signal. Microelectronic autogenerator devices for determining the thickness combine the simplicity and versatility of analog devices with the accuracy and immunity that characterize devices with a coded output. The application of the principle of "thickness-frequency" conversion based on microelectronic autogenerator transducers significantly reduces the cost of information-measuring systems, allows you to significantly reduce mass-size indicators, and increase the accuracy and sensitivity of information signal-to-frequency conversion [12-15].

FORMULATION OF THE PROBLEM

The purpose of the work is the creation and research of transducers for measuring the thickness of materials based on microelectronic transistor structures, in which the primary transducers are capacitive structures sensitive to changes in thickness with rectangular and round metal covers, which are also elements of autogenerators. Energy losses in the oscillating system of autogenerators are compensated by the energy of negative differential resistance, which allows converting the information signal about thickness into frequency. To achieve the set goal in the work, the following tasks must be solved:

1) conduct an analysis of existing scientific sources and justify the use of microelectronic transistor structures with negative differential resistance for the construction of transducers for determining the thickness of materials;
2) to develop mathematical models of thickness-sensitive transducers, which take into account the dependence of parameters of autogenerators and thickness-sensitive elements on changes in the thickness of materials and their influence on the output frequency of devices;

3) obtain analytical expressions of the parametric dependence of the transformation function and sensitivity on the thickness of the material;
4) develop conclusions from the conducted research.

MATHEMATICAL MODELS OF TRANSDUCERS FOR THICKNESS MEASUREMENT

Device for measuring the thickness of materials with a frequency output signal is built on the basis of a microelectronic transistor structure with a negative differential resistance, in which a capacitor with rectangular electrodes C1 acts as the primary element sensitive to thickness changes. In fig. 1 shows a diagram of a microelectronic autogenerator transducer for thickness measurement.

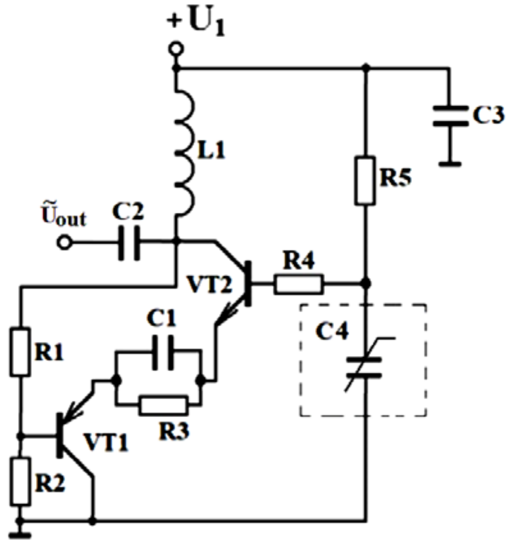

Figure 1 – Electric circuit of the autogenerator transducer for thickness measurement

It consists of two bipolar transistors VT1 and VT2 with different types of conductivity of the base region, which forms a descending section on the current-voltage characteristic at the output terminals of the transducer. The negative differential resistance corresponds to the falling section. The transducer is powered by a constant voltage source U1 through resistors R1-R2 and R4-R5. Capacitance C3 serves to block alternating voltage and prevents it from reaching the source of constant springs U1. Capacitor C2 serves to match the load (50 Ohms) to the antenna or power amplifier. The RC circuit, formed by the parallel connection of capacitor C1 and resistor R3, is placed between the emitter of the first bipolar transistor VT1 and the emitter of the second bipolar transistor VT2 and serves to thermally stabilize the operation of the microelectronic transducer for measuring the thickness of materials. The oscillating circuit of the device is formed by the passive inductance L1 and the total resistance capacitance that exists on the collector-collector electrodes of transistors VT1 and VT2. When the thickness of the material film located in the interelectrode space of the capacitor C1 changes, the active and reactive components of the total resistance on the collector-collector electrodes of the transistors VT1 and VT2 change, which leads to a change in the output frequency of the transducer [13, 15]. Sensitivity to changes in the thickness of materials is represented by a planar capacitor with rectangular metal electrodes, between which the measured material is located. The size of the capacitor's capacity is affected by the thickness of the dielectric, its dielectric constant and the area of the metal contacts. Taking edge effects into account empirically, the formula for the capacitance of a capacitor with rectangular electrodes is described by the expression [16]

$$C_n = \varepsilon\varepsilon_0 \frac{\alpha}{\pi} \ln\left(\frac{4d}{b} + \frac{b}{2d}\right), \qquad b \le \frac{d}{2}, \tag{1}$$

$$C_n = \varepsilon\varepsilon_0 \cdot \alpha \left(\frac{b}{d} + 1,21 - \frac{0,11d}{b} + 0,5\left(1 - \frac{d}{2b}\right)^6\right), \quad b \ge \frac{d}{2}, \tag{2}$$

where ε is the relative dielectric constant of the measured material when it completely fills the space between the electrodes, ε_0 – dielectric constant of vacuum, α - length, b – width of rectangular covers, d is the distance between them. Since in the interelectrode space, in addition to the measured material, there is a layer of air, the influence of this layer on the overall relative dielectric constant of the transducer can be obtained taking into account Lichtenecker's formula [18]. Taking this into account, the general relative dielectric constant of the primary transducer takes the form [17, 18]

$$\varepsilon = \frac{d\varepsilon_n\varepsilon_m}{\varepsilon_n h_m + d\left(d - h_m\right)}, \tag{3}$$

where ε_n is the relative dielectric constant of air, ε_m is the relative dielectric constant of the measured material, h_m is the thickness of the measured material. By substituting formula (3) into formula (1) and (2), we obtain the dependence of the total capacity of the primary transducer with rectangular electrodes on the measured thickness of the material [11, 19, 23]

$$C_n\left(h_m\right) = \left(\frac{d\varepsilon_n\varepsilon_m}{\varepsilon_n h_m + \varepsilon_m\left(d - h_m\right)}\right)\varepsilon_0\frac{\alpha}{\pi}\ln\left(\frac{4d}{b} + \frac{b}{2d}\right), \quad b \le \frac{d}{2}, \tag{4}$$

$$C_n\left(h_m\right) = \frac{d\varepsilon_n\varepsilon_m\varepsilon_0 a}{\varepsilon_n h_m + \varepsilon_m\left(d - h_m\right)}\left(\frac{b}{d} + 1,21 - \frac{0,11}{d} + 0,5\left(1 - \frac{d}{2b}\right)^6\right), \; b > \frac{d}{2}. \tag{5}$$

According to formula (4), we determine the change in the total capacity of the primary measuring transducer from the change in the thickness of the measuring material.

In general, it is described by expressions

$$\Delta C_n(h_m) = \frac{\partial C_n(h_m)}{\partial d}\Delta d(h_m) + \frac{\partial C_n(h_m)}{\partial \varepsilon_m}\Delta\varepsilon_m(h_m). \tag{6}$$

After performing the differentiation in formula (6), we obtain the expression

$$\begin{aligned}\Delta C_n(h_m) = \varepsilon_0\frac{a}{\pi}\Bigg\{\Bigg[&\frac{\varepsilon_n\varepsilon_m\ln\left(\frac{8d^2+b^2}{2bd}\right)}{\varepsilon_n h_m + \varepsilon_m(d-h_m)} - \frac{d\varepsilon_n\varepsilon_m^2\ln\left(\frac{8d^2+b^2}{2bd}\right)}{\left(\varepsilon_n h_m + \varepsilon_m(d-h_m)\right)^2} + \\ &+ \frac{\left(2d - \sqrt{8d^2+b^2}\right)\varepsilon_n\varepsilon_m}{\sqrt{8d^2+b^2}\left(\varepsilon_n h_m + \varepsilon_m(d-h_m)\right)}\Bigg]\Delta d(h_m) + \ln\left(\frac{4d}{b} + \frac{b}{2d}\right)\times \\ &\times\left[\frac{\varepsilon_n d}{\varepsilon_n h_m + \varepsilon_m(d-h_m)} - \frac{d^2\varepsilon_n\varepsilon_m}{\varepsilon_n h_m + \varepsilon_m(d-h_m)}\right]\Delta\varepsilon_m(h_m)\Bigg\}.\end{aligned} \tag{7}$$

We will carry out a similar operation according to formula (5), thus obtaining the formula

$$\Delta C_n(h_m)=\varepsilon_0 a\left\{\left[\frac{\varepsilon_n\varepsilon_m}{\varepsilon_n+\varepsilon_m(d-h_m)}-\frac{d\varepsilon_n\varepsilon_m^2}{\left(\varepsilon_n+\varepsilon_m(d-h_m)\right)^2}\times\right.\right.$$
$$\left.\times\left(\frac{b}{d}-1,21-\frac{0,11d}{b}+0,5\left(1-\frac{d}{2b}\right)^6\Delta d(h_m)\right)\right]+\left[\frac{d\varepsilon_n\varepsilon_m}{\varepsilon_n+\varepsilon_m(d-h_m)}\times\right.$$
$$\left.\times\left(-\frac{b}{d^2}-\frac{0,11}{b}+3\left(1-\frac{d}{2b}\right)^5\frac{1}{2b}\right)\right]\Delta d(h_m)+\left[\frac{d\varepsilon_n}{\varepsilon_n+\varepsilon_m(d-h_m)}-\right.\tag{8}$$
$$\left.\left.-\frac{d^2\varepsilon_n\varepsilon_m}{\left(\varepsilon_n+\varepsilon_m(d-h_m)\right)^2}\times\left(\frac{b}{d}+1,21-\frac{0,11d}{b}+0,5\left(1-\frac{d}{2b}\right)^6\right)\Delta\varepsilon_m(h_m)\right]\right\}.$$

Let's move on to the definition of the parametric dependence of the output frequency of the transducer on the parameters of sensitivity to the change in the thickness of the material of the container and the parameters of the autogenerator. When solving this problem, it is necessary to consider the transformation of the change in the energy of the constant electric field in the primary measuring capacity when the thickness of the material changes into the energy of the variable electric field at the output of the device. To do this, we will determine the efficiency of the device. First, the change in the thickness of the material is converted into the energy of the constant electric field in the measuring capacitor, which is the input energy for the autogenerator. In the future, the energy of the constant electric field of the capacitor is transformed into the energy of the alternating electric field, which is connected with the equivalent capacity of the oscillating circuit of the autogenerator. The efficiency factor of the autogenerator transducer has the form

$$\eta=\frac{P_{out}}{P_{in}}.\tag{9}$$

The output power is described by the expression

$$P_{out}=\frac{C_{ekv}U_{\sim}^2}{2t_1},\tag{10}$$

where C_{ekv} is the equivalent capacity of the oscillating circuit of the autogenerator, $U_{\sim}$ – output alternating voltage, t_1 is the period of oscillations of the variable output voltage. The input power is described by the formula

$$P_{in}=\frac{C_n(h_m)U_{=}^2}{2t_2},\tag{11}$$

where $U_{=}$ is the constant voltage on the measuring capacitor, t_2 – the time of change in the thickness of the measuring material. Therefore, the efficiency factor of the device takes the form

$$\eta=\frac{C_{ekv}U_{\sim}^2t_2}{t_1C_n(h_m)U_{=}^2},\tag{12}$$

It is determined from formula (12). C_{ekv} , which is described by the expression

$$C_{ekv}=\frac{\eta t_1C_n(h_m)U_{=}^2}{U_{\sim}^2t_2},\tag{13}$$

On the other hand, the equivalent capacity can be determined from the formula of the resonance frequency of the autogenerator, which has the form [13, 15]

$$F_0 = \frac{1}{2\pi R_g C_{ekv}} \sqrt{\frac{R_g^2 C_{ekv}}{L} - 1}\,, \tag{14}$$

where R_g – negative differential resistance in the oscillating circuit, L – circuit inductance. From expression (14), we obtain a quadratic equation from which we determine C_{ekv}

$$\left(4\pi^2 F_0^2 R_g^2 L\right) C_{ekv}^2 - R_g^2 C_{ekv} + L = 0\,. \tag{15}$$

Let's enter the notation

$$n_1 = 4\pi^2 F_0^2 R_g^2 L\,, \tag{16}$$

$$n_2 = R_g^2\,, \tag{17}$$

$$n_3 = L\,, \tag{18}$$

$$n_4 = C_{ekv} = \frac{\eta t_1 C_n(h_m) U_=^2}{U_\sim^2 t_2}\,, \tag{19}$$

then C_{ekv} from equation (15) is equal to

$$C_{ekv} = \frac{n_2 \pm \sqrt{n_2^2 - 4 n_1 n_3}}{2 n_1}\,. \tag{20}$$

Equating expression (20) to expression (13), we obtain the equation for determination F_0, which looks like

$$n_1 = \frac{n_2}{n_4} - \frac{n_3}{n_4^2}\,. \tag{21}$$

By substituting the values of expressions (16)-(19) into formula (21), we obtain the equation

$$4\pi^2 R_g^2 L F_0^2 = \frac{R_g^2 U_\sim^2 t_2}{\eta t_1 C_n(h_m) U_=^2} - \frac{U_\sim^4 t_2^2 L}{\eta^2 C_n^2(h_m) U_=^4 t_1^2}\,. \tag{22}$$

From equation (22), we determine the parametric dependence of the output frequency of the device on the parameters of the primary transducer and the autogenerator parameters, where the value F_0 there is a device conversion function, so

$$F_0(h_m) = \frac{1}{2\pi}\left[\frac{U_\sim^2 t_2}{\eta t_1 C_n(h_m) U_=^2 L} - \frac{U_\sim^4 t_2^2}{\eta^2 C_n^2(h_m) U_=^4 t_1^2 R_g^2}\right]^{1/2}. \tag{23}$$

The obtained formula (23) shows a simple way of calculating the device transformation function in comparison with the calculation method based on the equivalent circuit, which is significantly complicated and requires the solution of the Kirchhoff equations by a numerical method on a computer.

In fig. 2 shows the graphical dependence of the calculated and experimental curves of the device transformation functions.

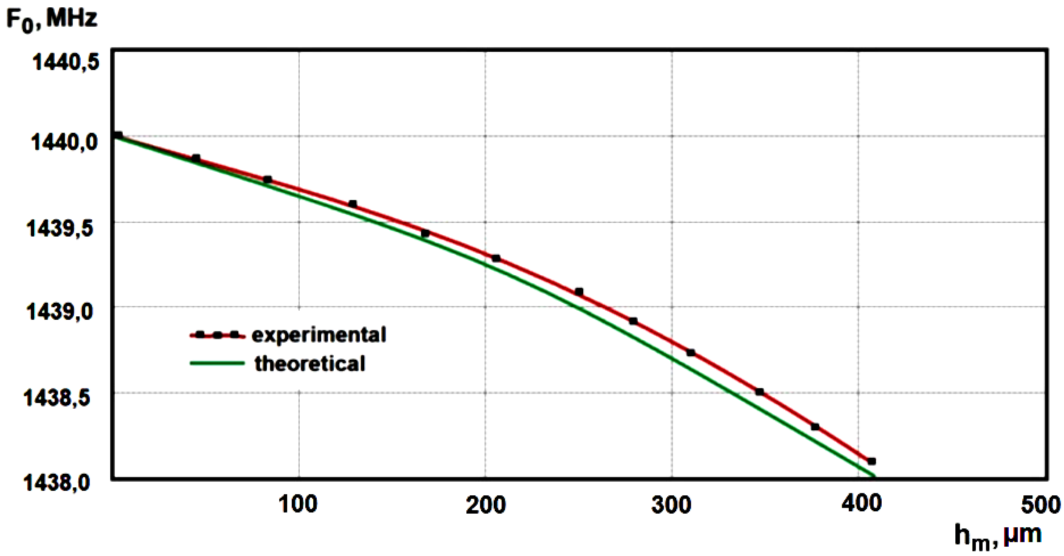

Figure 2 – Dependence of the transformation function on the thickness of the measured material

As can be seen from fig. 2, when changing the thickness of the material from 0 to 400 μm, the output frequency of the device varied from 1440.0 MHz to 1438.0 MHz.

The sensitivity of the device is determined by the derivative function (23) according to the thickness parameter h_m. As experimental studies show, the constant voltage $U_=$, as well as the output voltage, also depends on the thickness h_m, which must be taken into account when determining the sensitivity. Taking into account these remarks, the function (23) takes the form

$$F_0(h_m) = \frac{1}{2\pi}\left[U_\sim^2(h_m)C_n^{-1}(h_m)U_=^{-2}(h_m)n_5 - U_\sim^4(h_m)C_n^{-2}(h_m)U_=^{-4}(h_m)n_6\right]^{1/2}, \tag{24}$$

where

$$n_5 = \frac{t_2}{\eta t_1 L}, \tag{25}$$

$$n_6 = \frac{t_2^2}{\eta^2 t_1^2 R_g^2}, \tag{26}$$

then, taking into account (24)-(26), the sensitivity function of the device is described by the formula

$$\begin{aligned} S_{F_0}(h_m) &= \frac{1}{4\pi}\Big[U_\sim^2(h_m)C_n^{-1}(h_m)U_=^{-2}(h_m)n_5 - U_\sim^4(h_m)C_n^{-2}(h_m)\times \\ &\times U_=^{-4}(h_m)n_6\Big]^{-1/2}\left\{\left[2U_\sim(h_m)\frac{dU_\sim(h_m)}{dh_m}C_n^{-1}(h_m) + U_\sim^2(h_m)\times\right.\right. \\ &\times\left.\left(-C_n^{-2}(h_m)\frac{dC_n(h_m)}{dh_m}U_=^{-2}(h_m) - 2U_=^{-3}(h_m)\frac{dU_=(h_m)}{dh_m}C_n^{-1}(h_m)\right)\right]n_5 - \\ &-\left[U_\sim^4(h_m)\left(-2C_n^{-3}(h_m)\frac{dC_n(h_m)}{dh_m}U_=^{-4}(h_m) - 4U_=^{-5}(h_m)\times\right.\right. \\ &\left.\left.\left.\times\frac{dU_=(h_m)}{dh_m}C_n^{-2}(h_m)\right) + 4U_\sim^3(h_m)\frac{dU_\sim(h_m)}{dh_m}C_n^{-2}(h_m)U_=^{-4}(h_m)\right]n_6\right\}. \end{aligned} \tag{27}$$

The graph of sensitivity to changes in thickness is shown in Fig. 3.

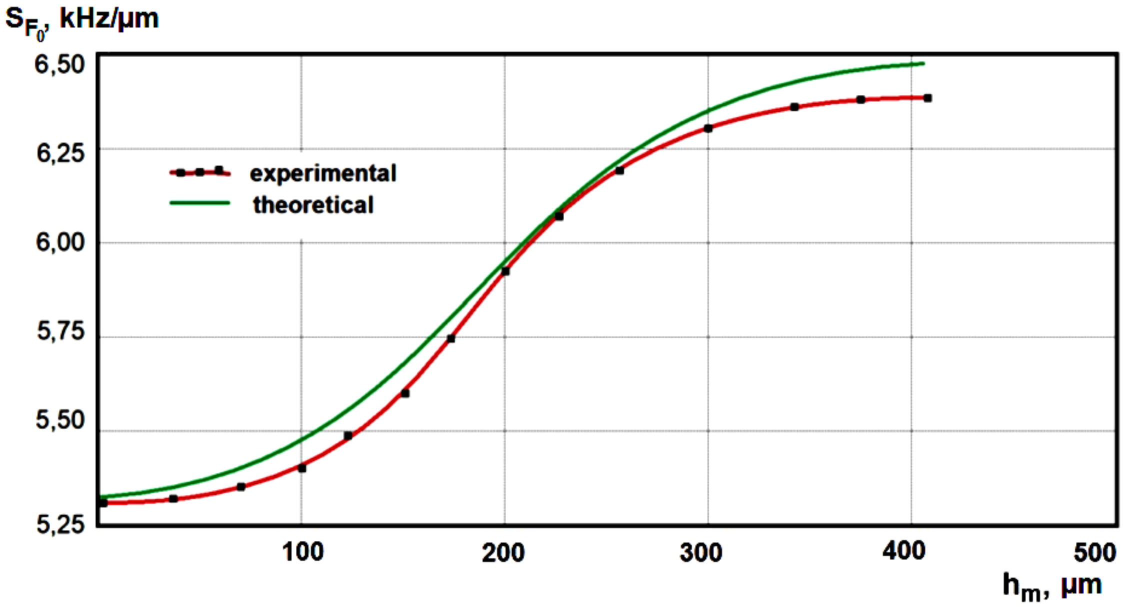

Figure 3 – Dependence of the sensitivity function on the thickness of the measured material

As can be seen from the graph (Fig. 3), the sensitivity of the device varied from 5.31 kHz/μm to 6.5 kHz/μm in the thickness range from 0 to 400 μm.

Let's move on to consider the parameters of the device for determining the thickness of the material based on a microelectronic autogenerator structure using a capacitor with round covers as the primary transducer. The electrical diagram of the device is shown in Fig. 4.

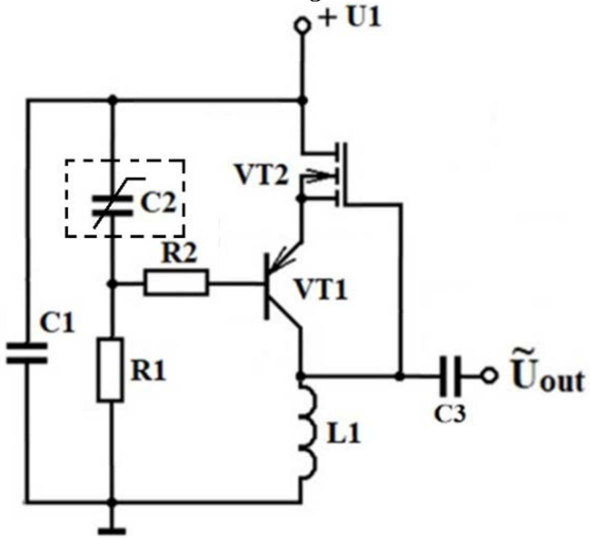

Fig. 4. Electric circuit of the autogenerator transducer for thickness measurement

The principle of operation of the autogenerator transducer presented in Fig. 4 is the same as the scheme in Fig. 1, except that bipolar and field-effect transistors are used in which the temperature coefficients have opposite signs, which reduces the influence of external temperature on the change in the output frequency of the transducer . This schematic solution simplifies the circuit of the autogenerator transducer. The capacity of a capacitor with round covers is described by the expression [20]

$$C_k(h_m) = \varepsilon_0 R \left[\frac{d \varepsilon_n \varepsilon_m}{\varepsilon_n h_m + \varepsilon_m (d - h_m)} \right] \left[\frac{\pi R}{d} + \left(\ln \frac{16 \pi R}{d} - 1 \right) \right], \tag{28}$$

where R is the radius of the round covers. The change in capacity when the thickness of the measured material changes is generally described by the formula

$$\Delta C_k(h_m) = \frac{\partial C_k(h_m)}{\partial d}\Delta d(h_m) + \frac{\partial C_k(h_m)}{\partial \varepsilon_m}. \tag{29}$$

After differentiation in formula (29), we obtain the expression

$$\begin{gathered}\Delta C_k(h_m) = \varepsilon_0 R\left\{\left[\left[\frac{\varepsilon_n\varepsilon_m}{\varepsilon_n h_m + \varepsilon_m(d-h_m)} - \frac{\varepsilon_n\varepsilon_m^2 d}{\left(\varepsilon_n h_m + \varepsilon_m(d-h_m)\right)^2}\right]\times\right.\right.\\ \times\left[\frac{\pi R}{d} + \left(\ln\frac{16\pi R}{d} - 1\right)\right] + \left(-\frac{\pi R}{d^2} + \frac{1}{d}\right)\left(\frac{d\varepsilon_n\varepsilon_m}{\varepsilon_n h_m + \varepsilon_m(d-h_m)}\right)\Bigg]\times\\ \times\Delta d(h_m) + \left[\left(\frac{d\varepsilon_n}{\varepsilon_n h_m + \varepsilon_m(d-h_m)} - \frac{\varepsilon_n\varepsilon_m d(d-h_m)}{\left(\varepsilon_n h_m + \varepsilon_m(d-h_m)\right)^2}\times\right.\right.\\ \left.\left.\left.\times\left(\frac{\pi R}{d} + \left(\ln\frac{16\pi R}{d} - 1\right)\right)\right)\right]\Delta\varepsilon_m(h_m)\right\}.\end{gathered} \tag{30}$$

The conversion function for the device that is submitted to Fig. 4, is determined analytically as for the previous case considered above. Its formula is described by an expression

$$F_0(h_m) = \frac{1}{2\pi}\left[\frac{U_{\sim}^2 t_2}{\eta C_k(h_m) U_{=}^2 t_1 L} - \frac{U_{\sim}^4 t_2^2}{\eta^2 C_k^2(h_m) U_{=}^4 t_1^2 R_g^2}\right]^{1/2}. \tag{31}$$

Figure 5 shows the graphical dependence of the calculated and experimental curves of the device's transformation function.

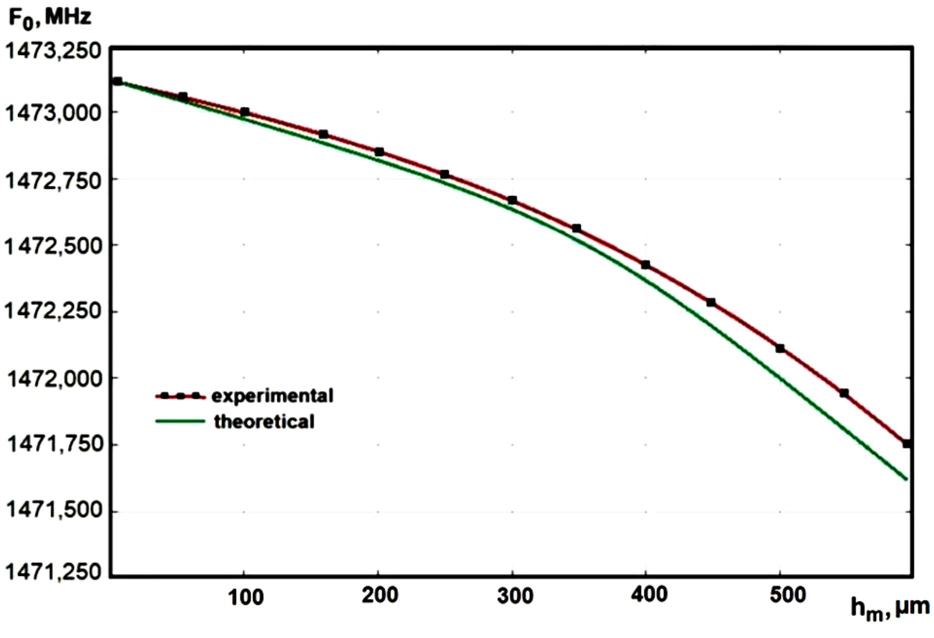

Figure 5 – Dependence of the transformation function on the thickness of the measured material

As can be seen from Fig. 5, when the thickness of the material changes from 0 to 600 µm, the output frequency varied from 1473.185 MHz to 1471.750 MHz.

The sensitivity of the device is determined by the derivative of the parameter h_m functions (31). At the same time, it is necessary to take into account the dependence of the output voltage U~, the constant voltage on the capacitor $U_{=}$ from the parameter h_m in addition to the main dependence of the capacitor capacity Ck. Thus, the transformation function (31) takes the form

$$F_0(h_m) = \frac{1}{2\pi}\left[U_{\sim}^2(h_m)C_k^{-1}(h_m)U_{=}^{-2}(h_m)n_5 - U_{\sim}^4(h_m)C_k^{-2}(h_m)U_{=}^{-4}(h_m)n_6\right]^{1/2}. \quad (32)$$

Then the sensitivity of the device according to the function (32) is described by the expression

$$\begin{aligned} S_{F_0}(h_m) = {} & \frac{1}{4\pi}\left[U_{\sim}^2(h_m)C_k^{-1}(h_m)U_{=}^{-2}(h_m)n_5 - U_{\sim}^4(h_m)C_k^{-2}(h_m)\times\right. \\ & \left.\times U_{=}^{-4}(h_m)n_6\right]^{-1/2}\left\{\left[2U_{\sim}(h_m)\frac{dU_{\sim}(h_m)}{dh_m}C_k^{-1}(h_m) + U_{\sim}^2(h_m) -\right.\right. \\ & \left.\left. - C_k^{-2}(h_m)\frac{dC_k(h_m)}{dh_m}U_{=}^{-2}(h_m) - 2U_{=}^{-3}(h_m)\frac{dU_{=}(h_m)}{dh_m}C_k^{-1}(h_m)\right)\right]n_5 - \\ & -\left[U_{\sim}^4(h_m)\left(-2C_k^{-3}(h_m)\frac{dC_k(h_m)}{dh_m}U_{=}^{-4}(h_m) - 4U_{=}^{-5}(h_m)C_k^{-2}(h_m)\times\right.\right. \\ & \left.\left.\times\frac{dU_{=}(h_m)}{dh_m}\right) + 4U_{\sim}^3(h_m)\frac{dU_{\sim}(h_m)}{dh_m}C_k^{-2}(h_m)U_{=}^{-4}(h_m)\right]n_6\Bigg\}. \end{aligned} \quad (33)$$

The graph of sensitivity to changes in thickness is shown in Fig. 6.

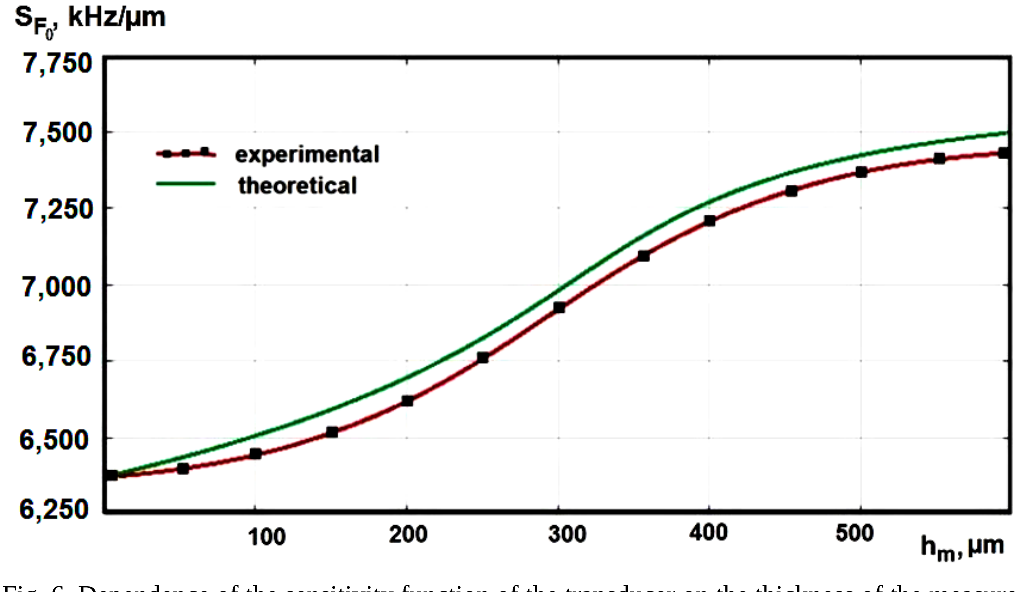

Fig. 6. Dependence of the sensitivity function of the transducer on the thickness of the measured material

As can be seen from the graph (Fig. 6), the sensitivity of the device was from 0 to 600 μm in the thickness range from 6.35 kHz/μm to 7.50 kHz/μm.

Frequency range of autogenerator transducers for thickness measurement with the frequency output signal selected from 1400 MHz to 1500 MHz. The L frequency range is used for equipment operating in the frequency range from 1.0 GHz to 2.0 GHz (ground terminals, Inmarsat systems, wireless audio and video equipment) [21, 22]. Experimental studies of the signal spectrum were carried out using the TinySA ULTRA radio frequency spectrum analyzer. In fig. 7 presents the radio frequency spectrum of autogenerator transducers for thickness measurement with a frequency output signal, the transmission frequency is 1438.5 MHz.

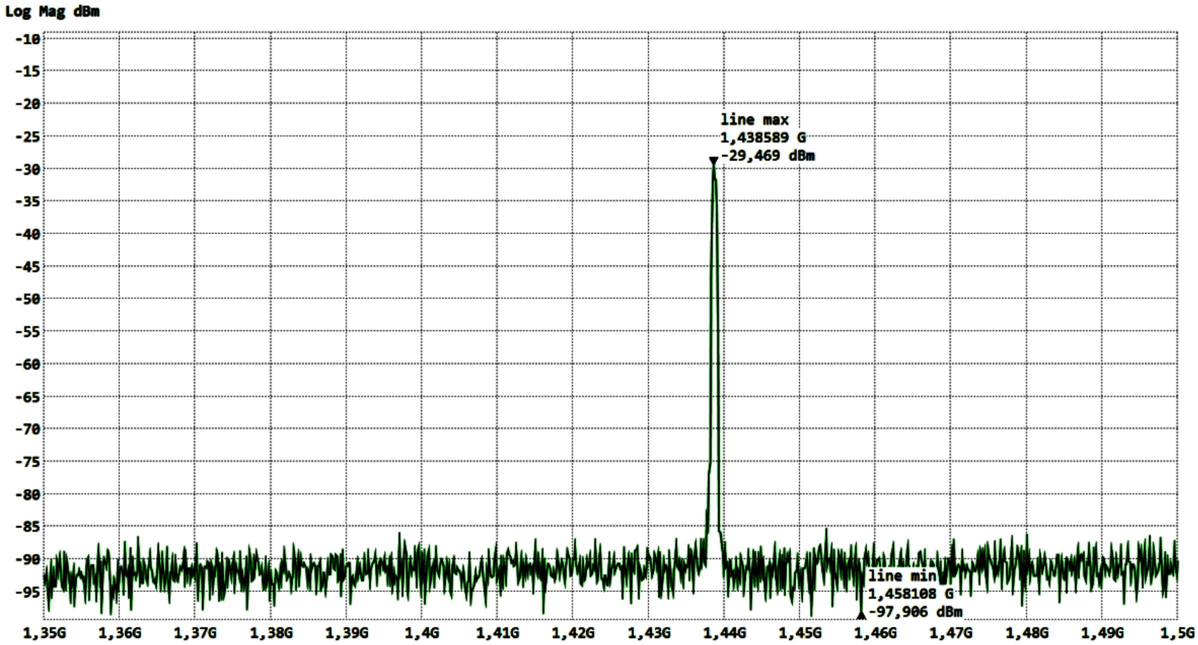

Figure 7 – Spectrum of the output signal of the transducer for thickness measurement with a frequency output signal

CONCLUSIONS

1. The main characteristics of devices for measuring the thickness of materials with a frequency output signal, the design of which is built on the basis of transistor structures with negative differential resistance, are proposed and investigated. The primary thickness measuring elements are capacitors with rectangular and round covers, which are passive elements of the autogenerator, which simplifies the design of materials thickness measuring devices.
2. Mathematical models of devices have been developed based on the principle of converting the energy of a constant electric field into the energy of an alternating electric field, which made it possible to obtain the conversion functions and sensitivity of the devices without using the complex method of obtaining Kirchhoff equations from the equivalent circuits of transducers and their calculation by numerical methods on modern computers. It is shown that the main contribution to the change in the conversion functions and sensitivity is made by the change in the thickness of the measuring material, which causes a change in the equivalent capacity and negative differential resistance of the oscillating system of autogenerators, which, in turn, leads to a change in the output frequency of the devices. The sensitivity of thickness measuring devices varies from 5.31 kHz/μm to 7.5 kHz/μm in the thickness range from 0 to 500 μm.
3. The calculated analytical expressions of the conversion and sensitivity functions clearly demonstrate the influence of each element of the primary transducers and autogenerator elements on the output frequency of the devices. Thickness measuring devices with frequency output do not require analog-to-digital transducers and amplifiers for further processing of information signals, which makes information-measuring equipment cheaper. When the transducer works at ultra-high frequencies, it is possible to transmit information over a distance.

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ПАРАМЕТРИЧНІ АВТОГЕНЕРАТОРНІ ПЕРЕТВОРЮВАЧІ ДЛЯ ВИМІРЮВАННЯ ТОВЩИНИ МАТЕРІАЛІВ НА ОСНОВІ КОНДЕНСАТОРНИХ ЧУТЛИВИХ ЕЛЕМЕНТІВ

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