Optical transducers with frequency output

Osadchuk, Oleksandr, Osadchuk, Volodymyr, Osadchuk, Iaroslav, Kolimoldayev, Maksat, Komada, Paweł, et al.

Oleksandr V. Osadchuk, Volodymyr S. Osadchuk, Iaroslav O. Osadchuk, Maksat Kolimoldayev, Paweł Komada, Kanat Mussabekov, "Optical transducers with frequency output," Proc. SPIE 10445, Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2017, 104451X (7 August 2017); doi: 10.1117/12.2280892

Event: Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2017, 2017, Wilga, Poland

Optical transducers with frequency output

Oleksandr V. Osadchuk[*a], Volodymyr S. Osadchuk[a], Iaroslav O.Osadchuk[a], Maksat Kolimoldayev[b], Paweł Komada[c], Kanat Mussabekov[c]
[a]Vinnytsya National Technical University, Vinnytsa, Ukraine; [b]Institute of Information and Computational Technologies, Almaty, Kazakhstan; [c]Lublin University of Technology, Lublin, Poland

ABSTRACT

In this work the characteristics research of microelectronic transducers of optical radiation with a frequency output signal on the basis of a hybrid integrated circuit consisting of a bipolar and a field-effect transistor with a Schottky barrier is presented. The connection of an external inductance to electrodes a collector - drain allows to implement the auto generating device. The frequency of the device generation depends on power of optical radiation falling on photosensing elements as a photoresistor, photodiode and photosensing transistors switched on in a circuit of the self-excited oscillator. The impedance on electrodes the collector - drain of bipolar and field transistors has capacitive reactive part and negative active resistance, which compensates power losses in a tuning circuit of the device. On the base of a nonlinear equivalent circuit of the transducer on an alternating current the analytical expressions of function of transformation and equation of sensitivity are obtained. The sensitivity of optical transducers lays in a range from 25 kHz/μWt/cm^2 up to 150 kHz/μWt/cm^2.

Keywords: optical transducers, frequency output signal, negative resistance, photoreactive effect

1. INTRODUCTION

The characteristics of transducers determine accuracy and reliability of systems of a radio control, instruments of monitoring of technological processes, environmental properties, safety of operation of kernel, thermal, chemical installations, flying apparatuses, sea plants, carrier etc. In this connection to transducers, which measure the manifold information, the rigid requirements are advanced. These devices should be cost-effective, noise-resistant, to ensure high speed, sensitivity and measurement accuracy, to have whenever possible least overall dimensions and weight, to be compatible with modern PCs and to allow encoding the information in transfer time it on major distances.

Therefore one of perspective scientific directions in development of transducers offered in the work, is usage of dependence of reactive properties and negative resistance of semiconductor devices from influence of exterior physical quantities and making on this base a new class of radiomeasuring microelectronic transducers of optical radiation. In devices of such type there is a transformation of optical radiation to a frequency signal, that allows to create transducers on integrated technology and enables to boost speed, accuracy and sensitivity, to expand a range of measurands, to improve reliability, noise stability and long-time parameter stability[1-9]. Besides the integration on the single-crystal of transducer with the circuits of an information processing enables makings “intellectual” devices. Usage as information parameter of frequency allows to avoid application of amplifiers and A/D converters at an information processing, that reduces the cost price of systems of radiomonitoring and radio control[10-13]. Thus, on the agenda already today arises the necessity of development of qualitatively new theoretical approaches to making radiomeasuring microelectronic transducers, development of their circuits and constructions, experimental research of their characteristics and metrological parameters.

*osadchuk69@mail.ru

Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2017, edited by Ryszard S. Romaniuk, Maciej Linczuk, Proc. of SPIE Vol. 10445, 104451X
 · doi: 10.1117/12.2280892

2. THEORETICAL AND EXPERIMENTAL RESEARCHES OF THE CHARACTERISTICS OF MICROELECTRONIC TRANSDUCERS OF OPTICAL RADIATION

For construction of transducers of optical radiation it is necessary to develop the theory elements of photoreactive effect for sensitive elements as bipolar and field-effect transistors of transducers. The above mentioned effects understand as dependence of the impedance of bipolar and field-effect transistors from action of optical radiation. For determination in an analytical form of dependence of the impedance of sensitive elements from influence of optical radiation it is necessary to receive the solution of the transport equation and Poisson equation for alternating currents as allocation of injected carriers of a charge in base area of bipolar and in a channel of field-effect transistors, which depends on optical radiation.

The processes of influence of optical radiation on sensing bipolar structures, which cause the occurrence of photoreactive effect, are featured by the transport equation. Nevertheless in this case the transport equation becomes complicated at the expense of processes of generation of charge carriers and creation of an electric field in a basic area at the action of an alternating voltage on emitter and collector junctions.

In view of these processes the analytical expression of the impedance of an active zone of a crystal of the photosensing bipolar transistor[10-17] is obtained. According to the obtained expression in view of influence of elements, which do not fall into an active zone of a crystal are calculated and experimentally investigated dependencies of an active and reactive parts of the impedance of photosensitive element on power of optical radiation are researched which are presented on Fig. 1.

As it is visible from the plot, the change of reactive part from power of optical radiation makes 11,8 Om/μWt/cm^2. The similar calculations and experimental researches were carried out for determination of the impedance of a photosensing field-effect transistor, which have shown, that the change of reactive part from power of optical radiation makes 20 Om/μWt/cm^2. The fulfilled researches have shown that the change of parts of the impedance is essential and it allows to use these dependencies for construction transducers of optical radiation with frequency output.

On the base of photoreactive effect theoretical and experimental researches of the characteristics of optical transducers are given, in which the effect of interaction of optical radiation with the metal of a gate, base area and channel of bipolar and field transistors in a dynamic regime is taken into account, that allowed on the base of models to calculate the characteristics of transducers and to prove experimentally their adequacy to models[18, 19].

Designedly photosensing transducer consists of a gallium-arsenide field-effect transistor with a Schottky barrier and a bipolar transistor. This structure is the base for build-up of transducers because it ensures the regime of work in a range of superhigh frequencies, that it is very important for UHF optoelectronics. The electric circuit of the device is presented on Fig. 2.

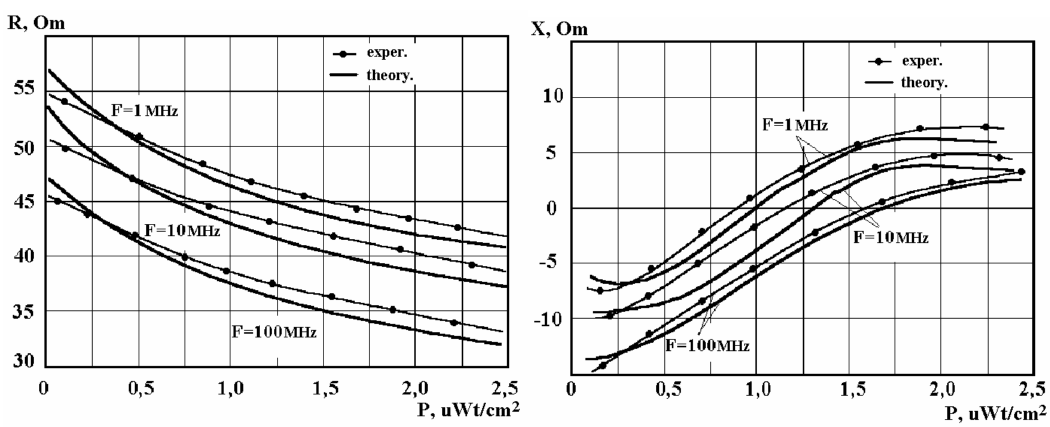

Figure 1. Dependence of active and reactive parts of impedance of bipolar transistor from power of optical radiation.

Theoretically and experimentally is proved that on electrodes the collector–drain of the offered structure exists negative resistance, which answers a falling section on a volt-ampere characteristic. The photosensing transducer feeds from sources of constant voltage U1. The circuit R_1C_1 produces an additional backward positive connection of an output with an input. Through resistance R_2, which is a sensitive element, the supply of the collector of the bipolar transistor and circuits a gate - drain of the field-effect transistor is carried out. Capacity C_2 realizes a block role, i.e. protects the source of a direct current U1 from currents of superhigh frequencies. The tuning circuit is created by passive inductance L_1 and capacity, which exists on electrodes a collector bipolar and drain of field transistors.

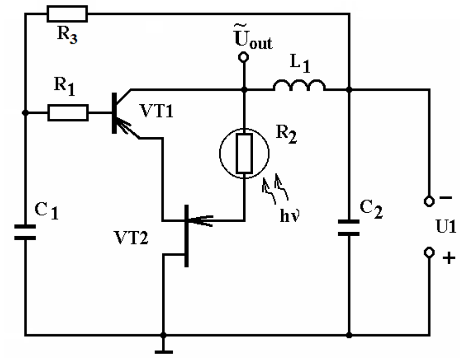

Figure 2. An electric circuit of the transducer on the base of bipolar and field transistors, which photosensing element is the photoresistor.

For learning the behavior of the photosensing transducer in a dynamic regime the dependencies of an active and reactive parts of impedance on electrodes of a collector – drain structure, frequency of generation, function of transformation and sensitivity from action of optical radiation are obtained. The calculations are made on the base of an equivalent circuit of bipolar and field transistors, which make the photosensing transducer (Fig. 3).

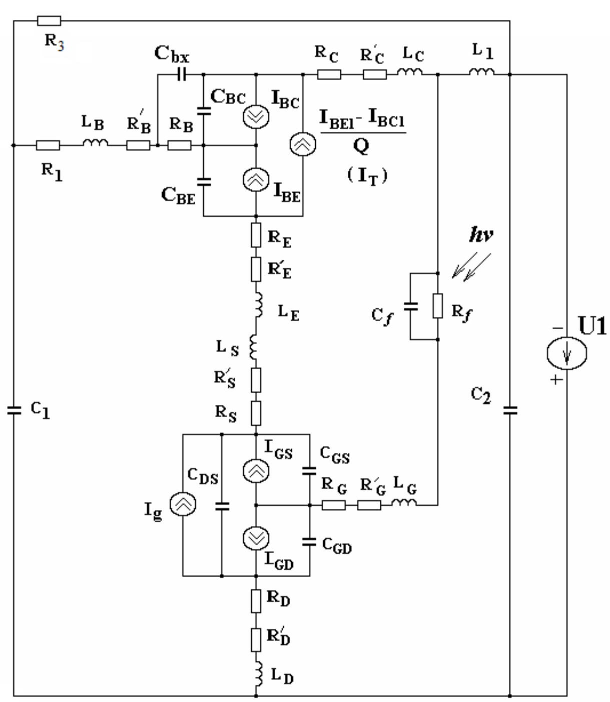

Figure 3. An equivalent circuit of the transducer on the base of bipolar and field transistors with a photoresistor.

The fulfilled researches have shown that an active component receives a negative value and a reactive one - a capacitate character. The connection of an external inductance to contact terminals the collector - drain of structure at negative values of an active part, when the power losses in a tuning circuit are compensated, allows to create the autogenerator of electric oscillations. During the action of a light on a photoresistor R_1 the change of an active and reactive parts of the impedance is carried out, and it in turn, changes the frequency of generation.

For determining the function of transformation it is necessary to find dependence of frequency of generation on power of falling optical radiation. It is possible to do it by solving a set of Kirchhoff equations, which is composed for alternating-current on the base of an equivalent circuit (Fig. 3). The solution of the set of Kirchhoff equations allows to receive the value of the impedance on electrodes a collector - drain of the transducer. At separating of the impedance into real and imaginary parts, it is not difficult to determine the equivalent capacity of a tuning circuit.

The function of transformation in this case has the form

$$F_0 = \frac{1}{4}\frac{\sqrt{2}\sqrt{\dfrac{R_f^2(P)C_f^2 + C_{gd}R_f^2(P)C_f - LC_{gd} - D}{LC_{gd}R_f^2(P)C_f^2}}}{\pi}, \tag{1}$$

where

$$D = \sqrt{(R_f^2(P)C_f^2 + C_{gd}R_f^2(P)C_f - LC_{gd})^2 + 4LC_{gd}R_f^2(P)C_f^2}$$

The sensitivity of the optical transducer is determined by the formula from (1)

$$S_P = \frac{1}{4}\frac{\sqrt{2}\left(\dfrac{\partial R_f(P)}{\partial P}\right)\left(A_2 + \sqrt{A_1} + LC_{gd}\right)}{\pi R_f^2(P)C_f\sqrt{A_1}\sqrt{-\dfrac{-A_2 + \sqrt{A_1} + LC_{gd}}{LC_{gd}R_f^2(P)C_f^2}}}, \tag{2}$$

where

$$A_1 = R_f^4(P)C_f^4 + 2R_f^4(P)C_f^4C_{gd} + 2LC_{gd}R_f^2(P)C_f^2 + $$
$$+C_{gd}^2R_f^4(P)C_f^4 - 2C_{gd}^2R_f^2(P)C_fL + L^2C_{gd}^2,$$

$$A_2 = R_f^2(P)C_f^2 - C_{gd}R_f^2(P)C_f.$$

The circuit of the photosensing transducer is manufactured on hybrid technology and consists of the bipolar transistor of the type KT3123BM and the gallium-arsenide transistor with a Schottky barrier of the type 3P602. The external inductance is manufactured by a method of an ion-beam deposition. On Fig. 4 are shown the theoretical and experimental dependencies of function of transformation of structure on the base of bipolar and field transistors, which photosensing element is the photoresistor. As it is visible from the plot, the divergence between theoretical and experimental curves is satisfactory, that enables to consider theoretical calculations to be exactly. The adequacy of the designed mathematical model is determined as a relative accuracy, which makes ±5%.

Experimentally was established that with increasing of power of a luminous flux from 0 μWt/cm^2 up to 80 μWt/cm^2 the frequency of generation is diminished from 857,3 MHz up to 849,6 MHz. The researches have shown that by selecting the regime of supply from a constant voltage, it is possible to receive a linear dependence of frequency of generation from power of an incident light. On Fig. 5 the theoretical and experimental dependencies of frequency of generation on environment temperature are presented.

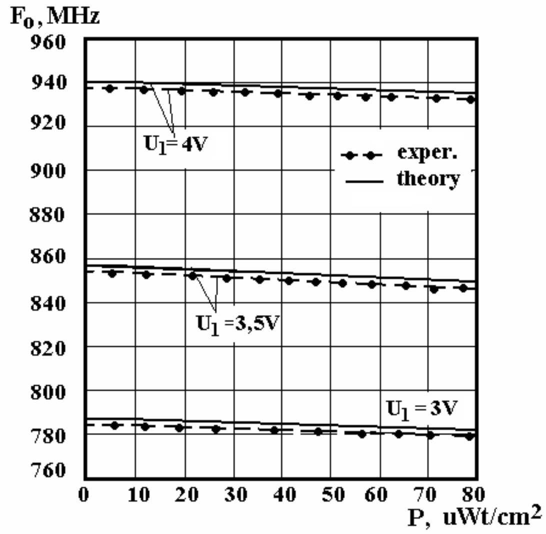

Figure 4. Theoretical and experimental dependencies of frequency generation from power of optical radiation.

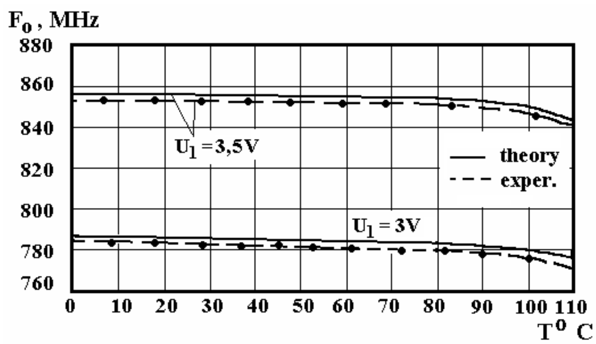

Figure 5. Dependence of frequency of generation on temperature.

An optimum supply voltage is the value 4 V, at which there is the least frequency change of generation in the range from 20 ^{0}C up to 80 ^{0}C. In the field of temperatures from 20 ^{0}C up to 50 ^{0}C is possible the most temperature stabile work of the transducer, when the sensitivity makes 146 kHz/μWt/cm^2 (Fig. 6).

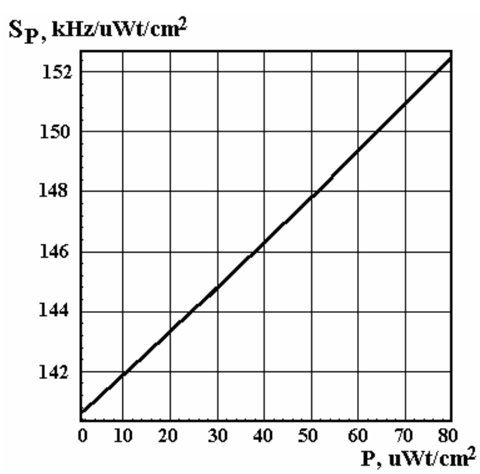

Figure 6. Dependence of the transducer sensitivity from power of optical radiation.

The further sensitization increasing, expansion of an operating range of frequencies of the transducer is possible under condition of usage of photodiodes as photosensing elements.

The transducer circuit on the base of bipolar transistor and field-effect transistor with a Schottky barrier, the photosensing element for which is the photodiode, is presented on Fig. 7.

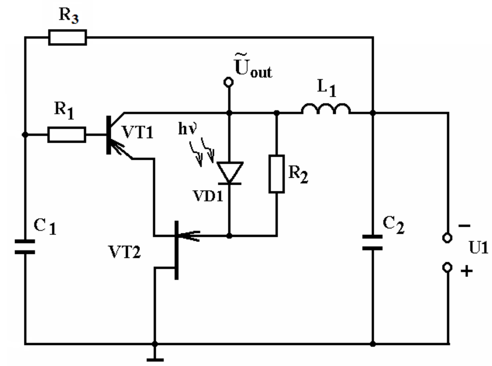

Figure 7. An electric circuit of the transducer with the photodiode.

The function of transformation is determined on the base of an equivalent circuit from calculation of the impedance on electrodes of the collector - drain phototransducer. The set of equations is solved by the Gauss method on a PC such as a Pentium at usage of the software package “Matlab 7.11”. The function of transformation of the photosensing transducer is determined by expression

$$F_0 = \frac{1}{4}\frac{\sqrt{2}\sqrt{\dfrac{\mathrm{B}_1+\sqrt{\mathrm{B}_1^2+4LC_{gd}R_d^2(P)C_d^2(P)}}{LC_{gd}R_d^2(P)C_d^2(P)}}}{\pi}, \tag{3}$$

where

$$\mathrm{B}_1 = R_d^2(P)C_d^2(P)+C_{gd}R_d^2(P)C_d(P)-LC_{gd}\,.$$

The equation of sensitivity of the frequency optical transducer with the photodiode is determined on the base of the formula (3)

$$\begin{aligned}
S_P = {} & \frac{1}{8}\sqrt{2}\Bigg(\Bigg(2R_d(P)C_d^2(P)\left(\frac{\partial R_d(P)}{\partial P}\right)+2R_d^2(P)C_d(P)\times\left(\frac{\partial C_d(P)}{\partial P}\right)+2C_{gd}R_d(P)C_d(P)\left(\frac{\partial R_d(P)}{\partial P}\right)+C_{gd}R_d^2(P)\times \\
& \times\left(\frac{\partial C_d(P)}{\partial P}\right)+\frac{1}{2}\Bigg(2A_1\Bigg(2R_d(P)C_d^2(P)\left(\frac{\partial R_d(P)}{\partial P}\right)+2R_d^2(P)C_d(P)\left(\frac{\partial C_d(P)}{\partial P}\right)+2C_{gd}R_d(P)C_d(P)\left(\frac{\partial R_d(P)}{\partial P}\right)+ \\
& +C_{gd}R_d^2(P)\left(\frac{\partial C_d(P)}{\partial P}\right)\Bigg)+8LC_{gd}R_d(P)C_d^2(P)\left(\frac{\partial R_d(P)}{\partial P}\right)+8LC_{gd}R_d^2(P)C_d(P)\left(\frac{\partial C_d(P)}{\partial P}\right)\Bigg)\Big/\sqrt{A_2}\Bigg)\Big/(LC_{gd}R_d^2(P)\times \\
& \times C_d^2(P))-\frac{2A_3\left(\dfrac{\partial R_d(P)}{\partial P}\right)}{LC_{gd}R_d^3(P)C_d^2(P)}-\frac{2A_3\left(\dfrac{\partial C_d(P)}{\partial P}\right)}{LC_{gd}R_d^2(P)C_d^3(P)}\Bigg)\Bigg/\left(\sqrt{\frac{A_3}{LC_{gd}R_d^2(P)C_d^2(P)}}\right),
\end{aligned} \tag{4}$$

where

$$A_1 = R_d^2(P)C_d^2(P)+C_{gd}R_d^2(P)C_d(P)-LC_{gd}\,,$$

$$A_2 = A_1^2 + 4LC_{gd}R_d^2(P)C_d^2(P),$$

$$A_3 = R_d^2(P)C_d^2(P) + C_{gd}R_d^2(P)C_d(P) - LC_{gd} + \sqrt{A_2}\ .$$

Dependence of frequency of generation on power of optical radiation is introduced on Fig. 8. From the plot it is visible, that with the growth of optical radiation from 0 μWt/cm^2 up to 120 μWt/cm^2 is watched the increasing frequency of generation from a supply voltage. The frequency of generation is diminished with the growth of power of optical radiation, and the greatest frequency change of generation is watched at supply voltages and controls 3 V (Fig. 8). On Fig. 9 is shown the calculated according to (4) sensitivity dependence of the optical transducer on the power of optical radiation.

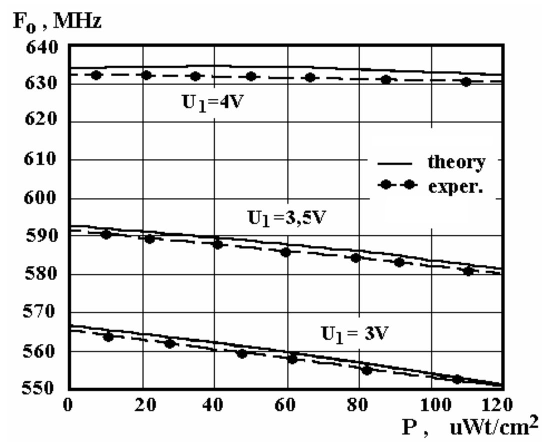

Figure 8. Theoretical and experimental dependencies of frequency generation from of optical radiation power.

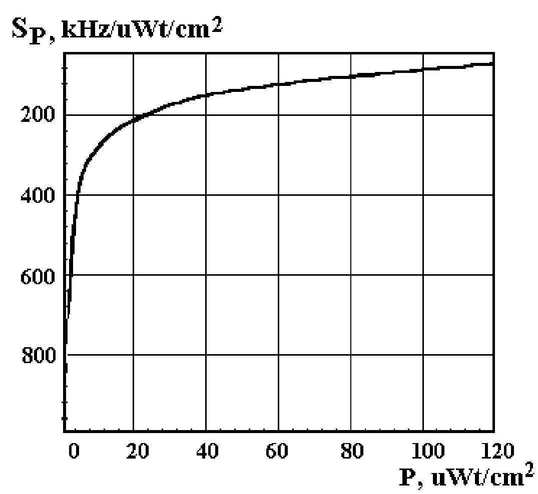

Figure 9. Sensitivity of the optical transducer with the photodiode.

The further expansion of frequency range of the transducer is possible under condition of usage as photosensing elements bipolar and field transistors. Designly photosensing transducer consists of the gallium-arsenide field-effect transistor with a Schottky barrier and bipolar transistor (Fig. 10)[17,19-27].

The volt-ampere characteristic of this structure has a section of negative resistance, which allows to compensate power losses in a tuning circuit created by an equivalent capacity of the collector - drain structure and an external inductance. The function of transformation is calculated from the set of equations composed on the base of a nonlinear equivalent circuit of the transducer.

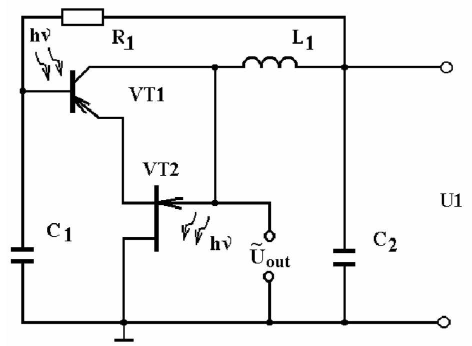

Figure 10. An electric circuit of the transducer on the base of field and bipolar transistors.

As well as in the previous cases, the solution of the set of Kirchhoff equations was carried out by the Gauss method on a PC with help of the software package "Matlab 7.11". From the set of equations the function of transformation is determined:

$$F_0 = \frac{1}{2}\frac{\sqrt{\dfrac{M_1 + C_{bc}(P)C_{be}(P)C_2 + C_{bc}(P)C_{be}(P)C_{ds}(P)}{L_1 C_{bc}(P)C_{be}(P)C_{ds}(P)C_2}}}{\pi} \tag{5}$$

where

$M_1 = C_{be}(P)C_{ds}(P)C_2 + C_{bc}(P)C_{ds}(P)C_2$,

C_{ds} - capacity of drain - source.

The equation of sensitivity is determined on a base (5):

$$S_P = \frac{1}{4}\Bigg(\Bigg(\Bigg(\left(\frac{\partial C_{be}(P)}{\partial P}\right)C_{ds}(P)C_2 + C_{be}(P)\left(\frac{\partial C_{ds}(P)}{\partial P}\right)C_2 + \left(\frac{\partial C_{bc}(P)}{\partial P}\right)C_{ds}(P)C_2 + C_{bc}(P)C_2\left(\frac{\partial C_{ds}(P)}{\partial P}\right) + \left(\frac{\partial C_{bc}(P)}{\partial P}\right)\times$$
$$\times C_{be}(P)C_2 + \left(\frac{\partial C_{be}(P)}{\partial P}\right)C_{bc}(P)C_2 + \left(\frac{\partial C_{bc}(P)}{\partial P}\right)C_{be}(P)\times C_{ds}(P) + \left(\frac{\partial C_{be}(P)}{\partial P}\right)C_{bc}(P)C_{ds}(P) +$$
$$+\left(\frac{\partial C_{ds}(P)}{\partial P}\right)C_{bc}(P)C_{be}(P)\Bigg)/\left(L_1 C_{bc}(P)C_{be}(P)C_{ds}(P)C_2\right) - \frac{A_1\left(\dfrac{\partial C_{bc}(P)}{\partial P}\right)}{L_1 C_{bc}^2(P)C_{be}(P)C_{ds}(P)C_2} - \frac{A_1\left(\dfrac{\partial C_{be}(P)}{\partial P}\right)}{L_1 C_{bc}(P)C_{be}^2(P)C_{ds}(P)C_2} -$$
$$-\frac{A_1\left(\dfrac{\partial C_{ds}(P)}{\partial P}\right)}{L_1 C_{bc}(P)C_{be}(P)C_{ds}^2(P)C_2}\Bigg)\Bigg/\left(\sqrt{\frac{A_1}{A_2}}\right), \tag{6}$$

where P - power of optical radiation and

$$A_1 = C_{be}(P)C_{ds}(P)C_2 + C_{bc}(P)C_{ds}(P)C_2 +$$
$$+C_{bc}(P)C_{be}(P)C_2 + C_{be}(P)C_{ds}(P)C_{bc}(P),$$

$$A_2 = L_1 C_{bc}(P)C_{be}(P)C_{ds}(P)C_2 ,$$

On Fig. 11 the dependence of frequency of generation from the radiated power is presented at different lengths of waves of the optical radiation. As it is visible from the plot, the best sensitivity can be received, if the wavelength is equal 0,7 microns. The sensitivity of the optical transducer at powers more than 10 μWt/cm^2 makes 25 kHz/μWt/cm^2.

The investigation of characteristics of optical transducers with an active inductive element on the base of field-effect transistors of types BFT92 and 3P602 has allowed to work of the device in a frequency band up to 3 GHz at values of sensitivity 15 kHz/μWt/cm^2. The measuring error of power of optical radiation makes ±0,52%.

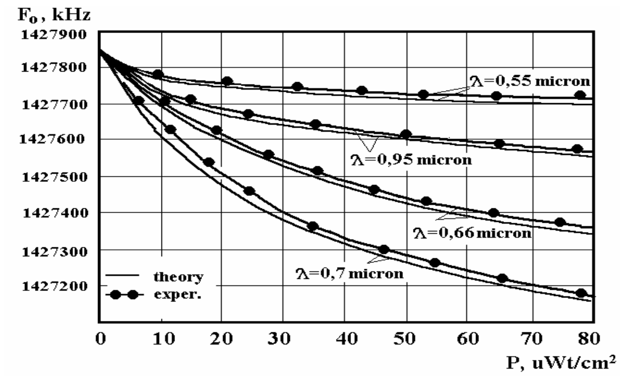

Figure 11. Dependence of generation frequency on power optical radiation.

3. CONCLUSIONS

The method of construction of radiomeasuring microelectronic transducers is offered on the base of photoreactive effect in sensing bipolar and field transistor structures, that has established premises for embodying transducers of optical radiation with a frequency output signal and microelectronic technology of manufacture. It considerably improves metrological and economical indexes of devices. The sensitivity of transducers of optical radiation lies in a range from 25 kHz/μWt/cm^2 up to 150 kHz/μWt/cm^2.

REFERENCES

[1] Hotra, Z. Yu., [Microelectronic sensors of physical quantities], League-Press, Lviv (2003).
[2] Novickiy, P. V., Knoring, V. G. and Gutnikov, V. S., [Digital devices with frequency sensors], Power, Leningrad (1970).
[3] Kholin, V. V., Chepurna, O. M., Shton, I. O., Voytsehovich, V. S., Azarov, O. D., Pavlov, S. V., Gamaleia, N. F. and Harasim, D., "Methods and fiber optics spectrometry system for control of photosensitizer in tissue during photodynamic therapy," Proc. of SPIE 10031, 1003138 (2016); doi:10.1117/12.2249259.
[4] Krioukov, E., Klunder, D. J. W., Driessen, A., Greve, J. and Otto, C., "Sensor based on an integrated optical microcavity," Optics Letters 27(7), 512-514 (2002); doi: 10.1364/OL.27.000512.
[5] Grattan, K. T. V. and Meggitt, B. T., [Optical Fiber Sensor Technology]. Kluwer Academic Publishers, London (1998).
[6] Michael, K. L., Taylor, L. C., Schultz, S. L. and Walt, D. R., "Randomly Ordered Addressable High-Density Optical Sensor Arrays," Anal. Chem. 70(7), 1242-1248 (1998); doi: 10.1021/ac971343r.
[7] Zabolotna, N. I., Pavlov, S. V., Radchenko, K. O., Stasenko, V. A., Wójcik, W. and Kussambayeva, N., "Diagnostic efficiency of Mueller-matrix polarization reconstruction system of the phase structure of liver tissue," Proc. of SPIE 9816, 98161E (2015); doi:10.1117/12.2229018.
[8] Wojcik, W., Cakala, S., Kotyra, A., Smolarz, A., "Analysis of the operation of an electrooptical Pockels effect sensor," Proc. SPIE 3189, 110-121 (1997).
[9] Wojcik, W., Kotyra, A., Przylucki, S., Smolarz, A. and Szymczak, J.T., "Evanescent field absorption sensor," Proc. SPIE 3054, 132-136 (1997)
[10] Osadchuk, V. S., [Inductive effect in semiconductor devices], High school, Kiev (1987).

[11] Osadchuk, V. S. and Osadchuk, A. V., [Reactive properties of transistors and transistor circuits], Universum-Vinnitsa, Vinnitsa (1999).
[12] Osadchuk, A. V., [Microelectronic frequency transducers on the base of transistor structures with negative resistance], Universum-Vinnitsa, Vinnitsa (2000).
[13] Osadchuk, V. S. and Osadchuk, A. V., "The Microelectronic Radiomeasuring Transducers of Magnetic Field with a Frequency Output," Electronics and Electrical Engineering 4(110), 67-70 (2011).
[14] Osadchuk, V. S. and Osadchuk, A. V., "Radiomeasuring Microelectronic Transducers of Physical Quantities," Proc. of the International Siberian Conference on Control and Communications (SIBCON), (2015).
[15] Osadchuk, A., Osadchuk, I., Smolarz, A. and Kussambayeva, N., "Pressure transducer of the on the basis of reactive properties of transistor structure with negative resistance," Proc. of SPIE 9816, 98161C (2015); doi: 10.1117/12.2229211.
[16] Osadchuk, O., Osadchuk, V. and Osadchuk, I., "The Generator of Superhigh Frequencies on the Basis Silicon Germanium Heterojunction Bipolar Transistors," Proc. of 13th International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET), 336-338 (2016); doi: 10.1109/TCSET.2016.7452051.
[17] Osadchuk, A. V., "Research of photoreactive effect in the field-effect transistors," The bulletin of Vinnitsa polytechnic institute 3, 95-103 (2001).
[18] Tarnovskii, N. G., Osadchuk, V. S. and Osadchuk, A. V., "Modeling of the gate junction in GaAs MESFETs," Russian Microelectronics 29(4), 279-283 (2000); doi: 10.1007/BF02773276.
[19] Tarnovskii, N. G., Osadchuk, V. S. and Osadchuk, A. V. "Investigation of a Photogalvanic Effect Observed under Illumination of a Metal-Semiconductor Junction When the Optical Radiation is Completely Absorbed by the Metal Film," Journal of Communications Technology and Electronics 44(8), 932-938 (1999).
[20] Osadchuk, V. S., Osadchuk, A. V. and Osadchuk, E.V.," Semiconductor optical transducer," Patent of Russian Federation 2114490 H01L 31/08 (1998).
[21] Osadchuk, V. S., Osadchuk, A. V. and Osadchuk, E.V., "The optically controlled oscillator of harmonic oscillations," Patent of Ukraine 24474A H03C 3/36, (1998).
[22] Osadchuk, V. S., Rosumovskiy, P. B., Osadchuk, A. V. and Tarnovskiy M. G., "The high-speed transducer of optical signals," Patent of Ukraine 33402 AG02B 27/00 (2001).
[23] Osadchuk, V. S. and Osadchuk, A. V., "Research of the superhigh frequency oscillator with optical control," Proc. of the 10th International Conference Microcoll, 311-314 (1999).
[24] Gotra, Z., Golyaka, R., Pavlov, S. and Kulenko, S., "High resolution differential thermometer," Technology and Design in Electronic Apparatuses 6, 19-23 (2009).
[25] Cui, S., Pu, H., Lu, G., Wen, Z., Mattson, E. C., Hirschmugl, C., Gajdardziska-Josifovska, M., Weinert, M. and Chen, J., "Fast and Selective Room-Temperature Ammonia Sensors Using Silver Nanocrystal-Functionalized Carbon Nanotubes," ACS Appl. Mater. Interfaces 4(9), 4898-4904 (2012).
[26] Ki-Young Dong, Jinnil Choi, Yang Doo Lee, Byung Hyun Kang, Youn-Yeol Yu, Hyang Hee Choi and Byeong-Kwon Ju, "Detection of a CO and NH_3 gas mixture using carboxylic acid-functionalized single-walled carbon nanotubes," Nanoscale Research Letters 8(12), 1-6 (2013).
[27] Guo, S., Pan, X., Gao, H., Yang, Z., Zhao, J. and Bao, X., "Probing the Electronic Effect of Carbon Nanotubes in Catalysis: NH_3 Synthesis with Ru Nanoparticles," Chem. Eur. J. 16, 5379-5384 (2010).