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MULTIFREQUENCY GENERATOR, BASED ON CAPACITANCE EFFECT OF FIELD –EFFECT TRANSSISTOR STRUCTURE WITH NEGATIVE RESISTNCE

Investigation of multifrequency signals generator with complex spectral characteristic is carried out. Mathematical model has been obtained, experimental research and numerical modeling of multifrequency generator, based on capacitance effect of field-effect transistor structure with negative resistance have been performed.

***Key words**:mathematical model, transistor structure,negative resistance, multifrequency generator, equivalent capacitance.*

Actuality of the subject of the research

Actual problem of modern radioengineering is development and investigation of complex multifrequency signals generators with the preset spectral characteristic or noise-like signals [1]. Such generators are used for enhancement of noise immunity in radiocommunication systems [2], as well as, for transmission of discrete information with spectrum broadening by means of random and multifrequency signals [3]. In measuring engineering multifrequency generators, are used for investigation of frequency characteristics of two-ports and group time delay of users communication lines.

Conventional multifrequency generators consist of linear oscillatory circuit, non-linear oscillatory circuit, connected with it, and amplifier with limiting characteristic, that provides self-excitation of the system [4]. In nonlinear oscillatory circuit of the generator barrier capacitance of p-n-p junction (in particular, varicap) is used as variable reactive element.

Another approach to the development of multifrequency generators is to use capacitance effect of transistor structures with negative resistance [5]. This enables to perform the excitation of electric oscillations on one active element and control their frequency. Such approach considerably simplifies the construction of multifrequency generators and improves their functional and economic parameters.

The aim of the given research is to elaborate mathematic model of multifrequency generator on the basis of capacitance effect of field-effect transistor structure with negative resistance and experimental testing of this model.

Description of multifrequency generator functionning

Electric diagram of multifrequency generator based on field-effect transistor structure with negative resistance (FETSNR), developed by the authors, is shown in Fig. 1 [5]. Non-linear oscillating circuit is formed by reactive component of the impedance of transistor structure on drain-source electrodes of field-effect transistor VT2 and coil L1, linear circuit is formed from L1 and C3 elements.

Generator principle of operation is the following [5]: in nominal position of variable resistor R2 slide arm, the equivalent capacitance of field-effect transistor structure equals the capacitance of C3

capacitor, hence proper resonant frequencies of linear and non-linear oscillatory circuits are similar, that leads to generation of harmonic oscillation. If the position of R2 resistor slide arm changes, the equivalent capacitance of field-effect transistor structure changes, that leads to variation of resonant frequency of non-linear circuit. Deviations of linear circuit from resonant frequency are not great, that is why, the beating of two, close by frequency, oscillations occur in the generator. Frequencies of these oscillations enter the bandwidth of linear circuit L1 – C3 and the spectrum of output signal consists of two harmonics, that specifies two-frequency operation mode of the generator. Greater variation of R2 resistance produces rapid change of capacitance component of FETSNR impedance, that causes considerable deviation of resonant frequencies of linear and non-linear oscillatory circuits. Due to considerable non-linearity of dynamic voltage-current characteristic (VCC) of active element of the generator on field-effect transistors VT1 – VT2 the spectrum of the output signal has greater amount of harmonic components, which are the products of crossed combinations of two generated oscillations of different frequencies.

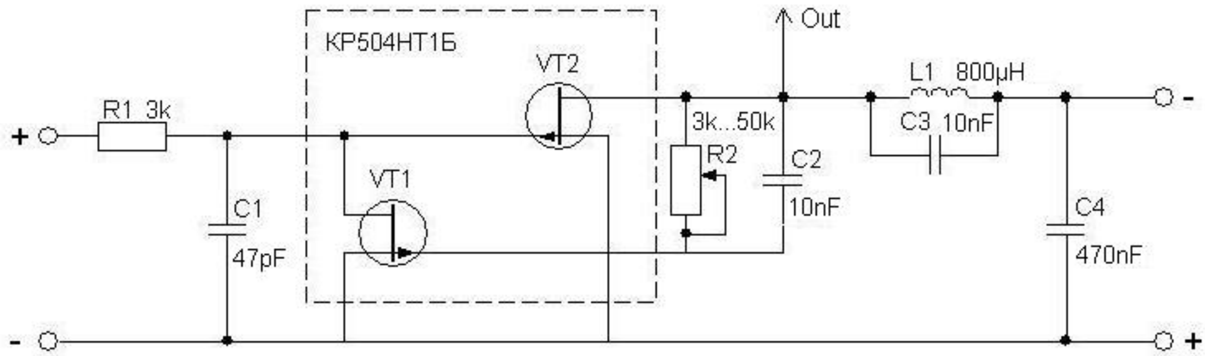


Fig. 1. Electric diagram of multifrequency generator, based on field-effect transistor structure with negative resistance

Mathematical model of multifrequency generator

Equivalent circuit of multifrequency generator, based on FETSNR is one of the form, shown in Fig. 2, non-linear resistance being power source, that takes into account the influence of the first current harmonic of the generator active element on linear oscillatory circuit [6]. Fig. 2 contains such notations: $i_C(u)$ – is controlled current source, which is the dependence of the current across the transistor structure with negative resistance on the voltage (it is defined by supply mode of the generator); C_{eq}, L_{eq} and R_{eq} – are correspondingly equivalent capacity, inductance and resistance of active losses of oscillatory circuit of the generator.

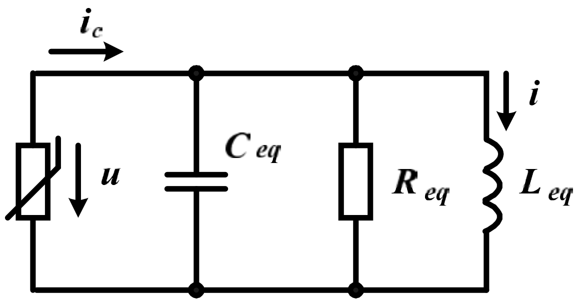


Fig. 2. Equivalent circuit of multifrequency generator on field-effect transistor

Differential equations for inductance current and voltage in the circuit in real time have the following form

$$\begin{cases} \dfrac{di}{dt} = \dfrac{1}{L}u, \\ \dfrac{du}{dt} = \dfrac{1}{C}\left[i_B - i - \dfrac{u}{R_{eqv}} \right]. \end{cases} \tag{1}$$

Nominal frequency of multifrequency generator on FETSNR in single frequency mode is close to resonant frequency of linear oscillatory circuit of the generator

$$\omega_{lin} = \omega_{non-lin} \approx \omega_0 , \qquad (2)$$

where $\omega_{non-lin}$ – is resonant frequency of non-linear oscillatory circuit.

Let us convert the system of differential equations (1) in normalized (dimensionless) time

$$t_N = \omega_0 t, \qquad (3)$$

where $\omega_0 = \frac{1}{\sqrt{L_{eq}C_{eq}}}$ – is resonant frequency of linear oscillatory circuit, taking into account the relation of secondary parameters of this circuit.

$$\rho = \omega_0 L_{eq} = \frac{1}{\omega_0 C_{eq}} = \sqrt{\frac{L_{eq}}{C_{eq}}}, \qquad (4)$$

$$Q = \frac{\rho}{R} = \omega_0 C_{eq} R. \qquad (5)$$

On condition (2) the system (1) is converted into second-order differential equation [6]

$$\frac{d^2 i}{dt_N^2} + 1 = i_T - \frac{1}{Q}\frac{di}{dt} + \nu i, \qquad (6)$$

where ν – is relative detuning of resonant frequency of non-linear oscillatory circuit relatively resonant frequency of linear oscillatory circuit of the generator, described by the relation

$$\nu = \frac{\omega_{lin}^2 - \omega_0^2}{\omega_0^2} \approx \frac{2(\omega_{lin} - \omega_0)}{\omega_0}. \qquad (7)$$

Solution of differential equation (6) can be shown as[6]

$$i = I_m \sin(t_H + \phi) = I_m \sin\psi , \qquad (8)$$

$$\frac{di}{dt_N} = I_m \cos(t + \phi) = I_m \cos\psi . \qquad (9)$$

Differential equations of amplitudes I_m and phase ϕ setting of generated oscillation have the form of [6]

$$\frac{dI_m}{dt_N} = \frac{1}{2} I_{1C} - \frac{I_m}{2Q}, \qquad (10)$$

$$\frac{d\phi}{dt_N} = \frac{1}{2}\frac{I_{1S}}{I_m} - \frac{1}{2}\nu , \qquad (11)$$

where I_{1C} and I_{1S} –are cosinusoid and sinusoid components of the first harmonic of function $i_T(u,t)$ decomposition into Fourier series.

For multifrequency FETSNR- based generator we may apply approximation of static VCC by such polynomial [7]

$$i_T(u) = \left(I_S + gU_S - hU_S^{\,3}\right) - \left(g - 3hU_S^{\,2}\right)\cdot(u-e) - 3hU_S(u-e)^2 + h(u-e)^3, \qquad (12)$$

where $u = U_m \cos\omega t$ – is the voltage in linear oscillatory circuit; U_S, I_S – are the coordinates of the middle of the falling section of voltage-current characteristic of field-effect transistor structure with negative resistance; g, h – are approximation factors, determined by experimental data, and

$$e(t) = E_m \cos\omega_{non-lin} t \qquad (13)$$

e (t) – is equivalent e.m.f. of the voltage in non-linear oscillatory circuit.

The amplitude of stationary oscillation of the generator in single-frequency mode is defined by the relation [7]

$$U_{ST} = \frac{2}{\sqrt{3}}\sqrt{\frac{g - 3hU_S^2}{h} + \frac{1}{hQ\rho\cos\phi_\beta}}. \tag{14}$$

Mean-square value of the amplitude of stationary oscillations of generator voltage in two-frequency mode is described by the relation

$$\tilde{U} = \left| \frac{\rho E_m \left[3hU_S^2 - g + \frac{3}{4}hU_{m0}^2 \right]}{\nu} \sin\phi \right|, \tag{15}$$

where U_{m0} – is the amplitude.of stationary oscillations of linear oscillatory circuit.

Multifrequency generator can operate in single-frequency mode. The value of critical detuning of resonant frequencies of non-linear and linear, oscillatory circuits is determined from the relation (15)

$$\nu_{cr} = \frac{E_m \rho \left[3hU_S^2 - g + \frac{3}{4}hU_{m0}^2 \right]}{U_{m0}}. \tag{16}$$

Equations of lower and upper limiting frequencies of generator operation range in single-frequency mode relatively resonant frequency of linear oscillatory circuit are

$$\omega_L = \omega_0 \left(1 - \frac{E_m}{2QU_{m0}} \right), \tag{17}$$

$$\omega_U = \omega_0 \left(1 + \frac{E_m}{2QU_{m0}} \right). \tag{18}$$

Results of mathematical modeling

The obtained analytical relations (1) – (18) comprise mathematical model of multifrequency FETSNR-based generator. In the theory of oscillations classical system of differential equations (1) is reduced to Van-der-Pole equation and is solved by one of asymptotic methods, in particular, of small parameter or slowly changing amplitudes. These methods impose strict limitations on output data, that is why, they are not, convenient fro investigation of multifrequency operation modes of such generator. That is why, the solution of the system of non-linear first-order differential equations (1), taking into account (4) - (7) and approximation equation (12)is performed using Runger-Kutt method of the 4 th order applying mathematical package of MathCad programs [8]. For this purpose function rkfixed, built in MathCad is used. To improve the accuracy of calculations, taking into account the peculiarity of Fourier fast transform in MathCad package, the number of counts 1024 was chosen. The results of numerical modeling of single and multifrequency modes are shown in Fig. 3 - 5 in the form of oscillograms, amplitude-frequency spectrum and operation point trajectory on phase plane of generated oscillations.

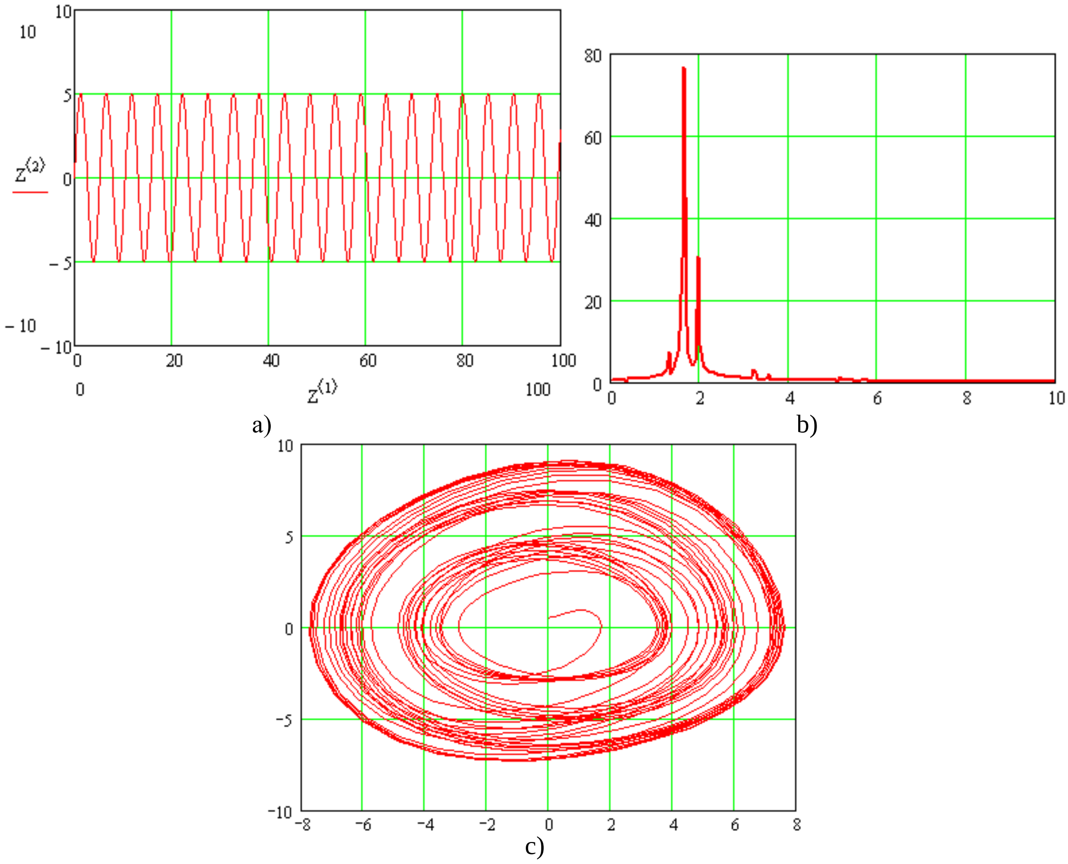


Fig. 3. Oscillograms (a) of amplitude-frequency spectrum (b) and phase plane (c) of generated oscillations in single-frequency mode

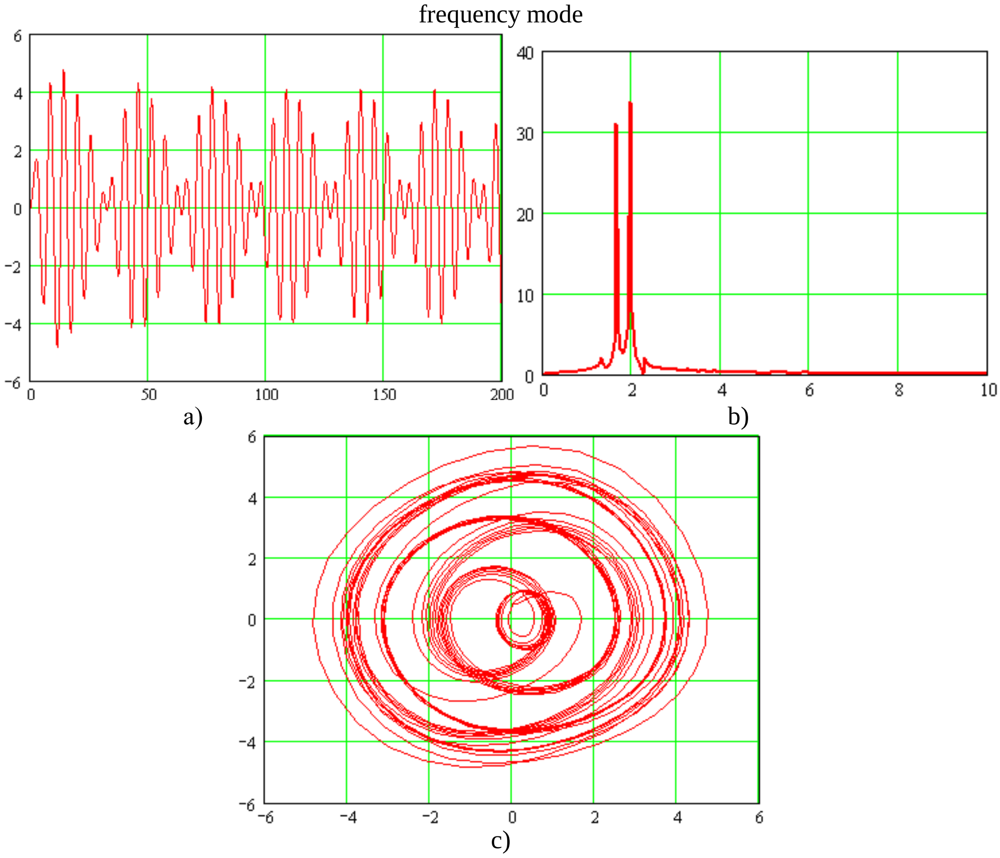
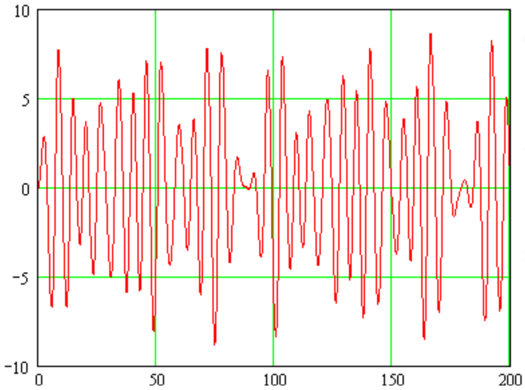


Fig. 4. Oscillograms (a) of amplitude-frequency spectrum (b) and phase plane (c) of generated oscillations in two-frequency mode



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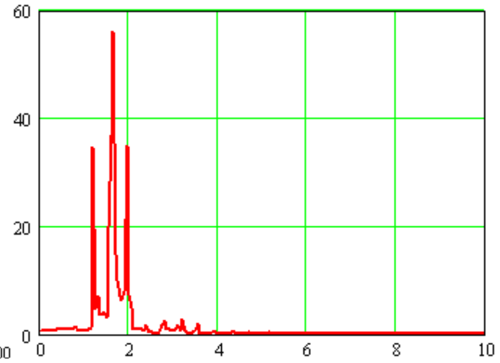

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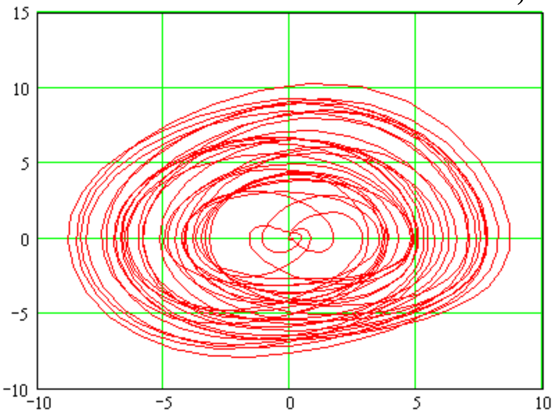
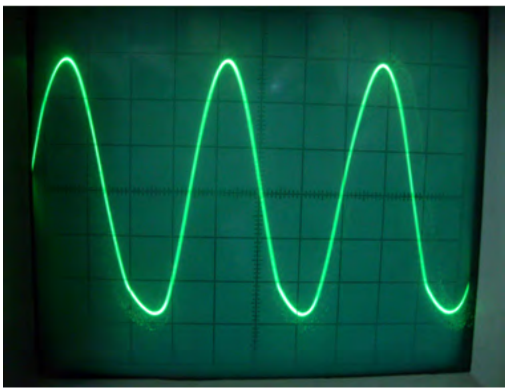


c)

Fig. 5. Oscillograms (a) of amplitude-frequency spectrum (b) and phase plane (c) of generated oscillations in three-frequency mode

The results o experimental research

Experimental model of multifrequency generator based on serial microassembly of field-effect transistors of КР504НТ1Б type was developed. Nominals of elements and polarity of supply voltage connection are shown in Fig. 1. Authors of the paper performed experimental research of operation modes of multifrequencies FETSNR – based generator, the results of which are shown in Fig. 6 – 10 [5]. Single-frequency and multifrequency operation modes were tested. As spectograms show, multifrequency modes with different number of generated oscillations are characterized by high spectral density near the harmonic of main oscillation with resonant frequency of parallel circuit L1C3.



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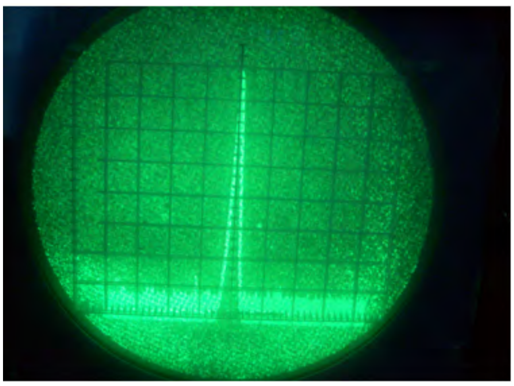

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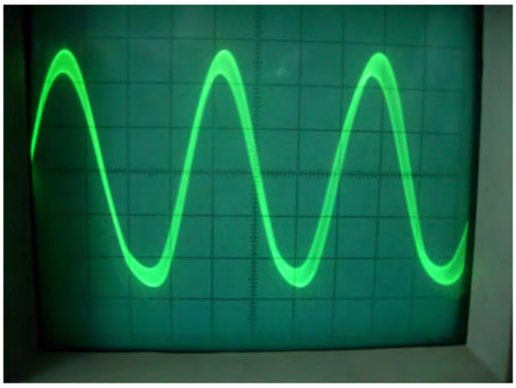
Fig. 6. Oscillogram (a) and spectrum (b) of generated oscillations in single-frequency mode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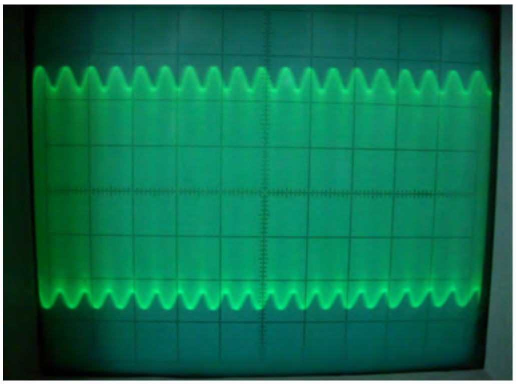
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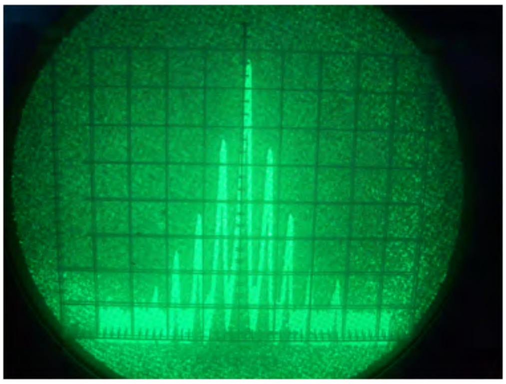
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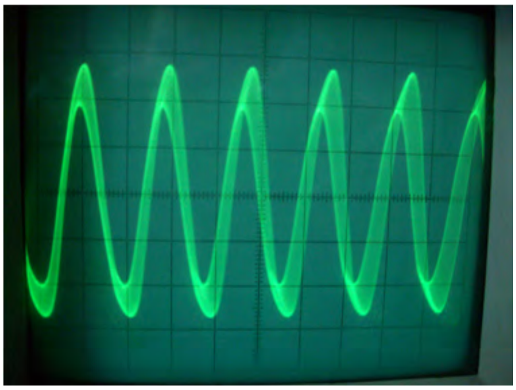
Fig. 7. Oscillograms of generated oscillations, synchronized by basic frequency (a) and by beating frequency (b), oscillations spectrum (c)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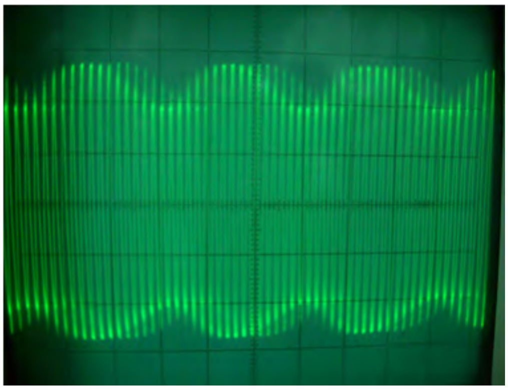
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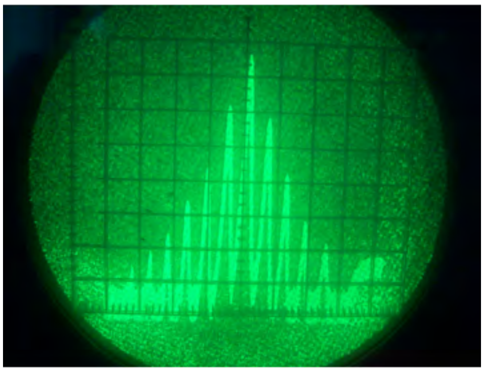
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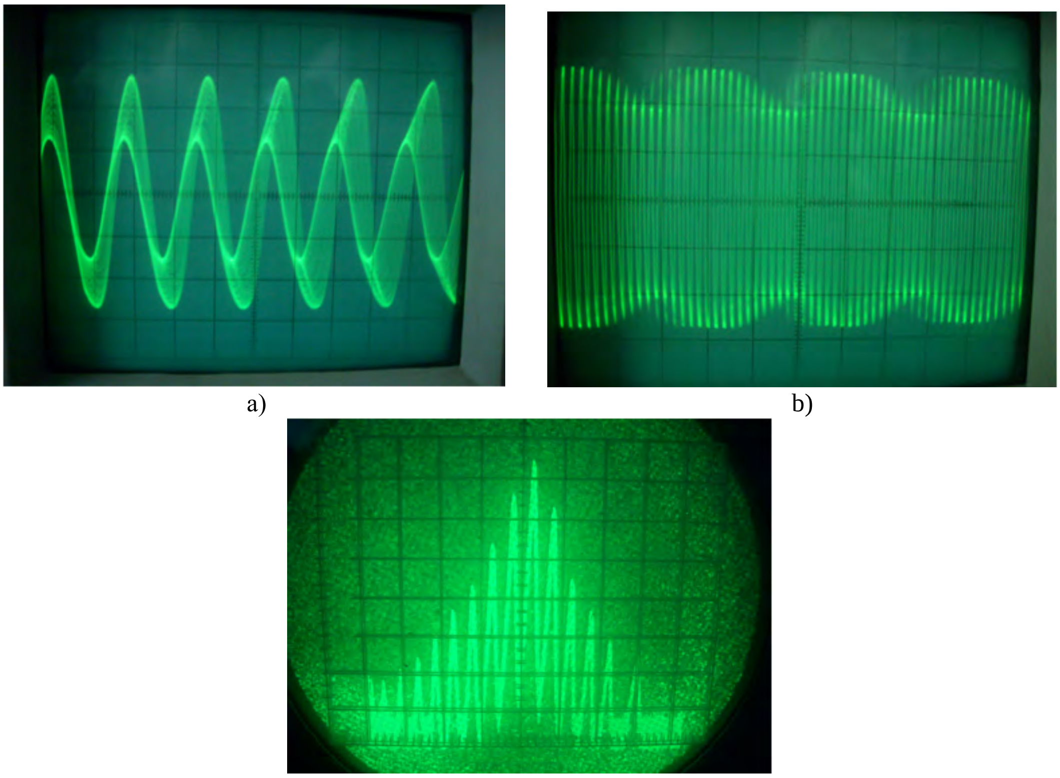
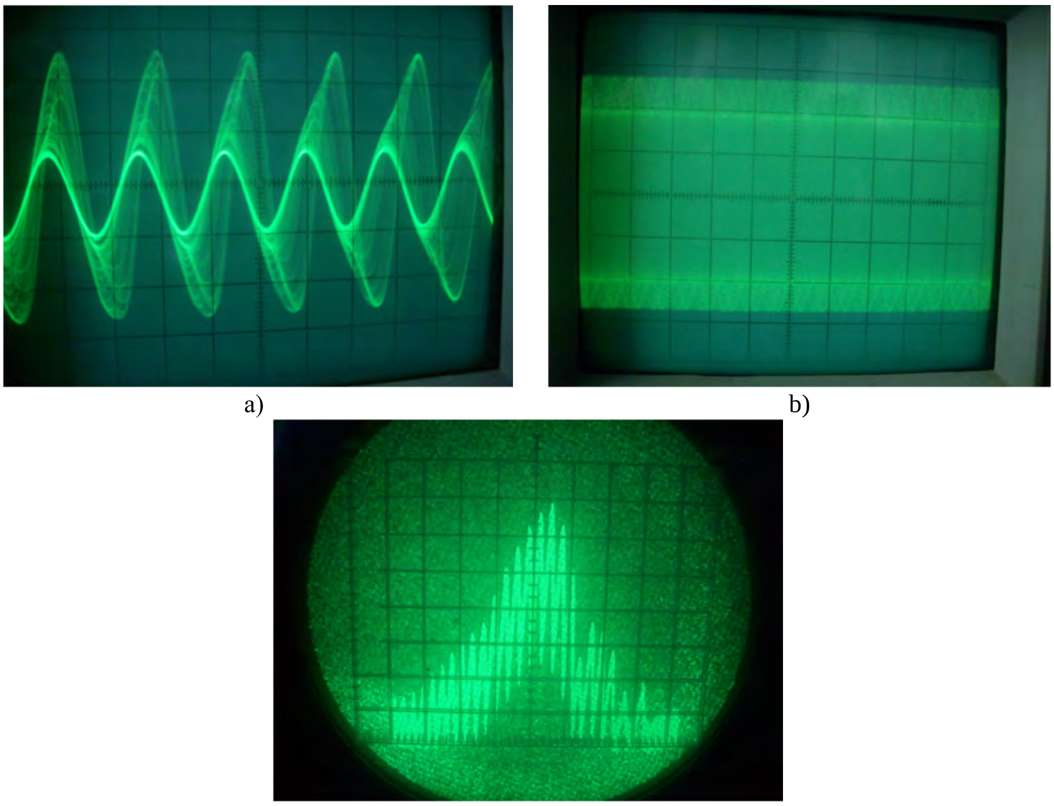
Fig. 8. Oscillograms of generated oscillations, synchronized by basic frequency (a) and by beating frequency (b), oscillations spectrum (c)



a) b)

c)

Fig. 9. Oscillograms of generated oscillations, synchronized by basic frequency (a) and by beating frequency (b), oscillations spectrum (c)



a) b)

c)

Fig. 10. Oscillograms of generated oscillations, synchronized by basic frequency (a) and by beating frequency (b), oscillations spectrum (c)

Conclusions

The paper contains analytical and experimental research of multifrequency generator, based on capacitance effect of field-effect transistor structure with negative resistance. Mathematical model of the generator with complex dynamics of generated oscillations has been developed. The results of numerical modeling and experimental research are suggested. Coincidence of the results obtained prove the adequacy of the developed mathematical model. As the drawback of numerical modeling in MathCad program package we should note the lack of the possibility to investigate the operation modes of the generator above three generated oscillations by means of obtained relations.

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