Paper

Optical control of semiconductor synchronized microwave oscillators in the power suppression mode

Dmitri A. Usanov, Alexander V. Skripal, and Anton V. Abramov

Abstract — The influence of optical radiation on the performance of the synchronized microwave Gunn-diode oscillator in the coherent signals subtraction mode has been described theoretically and investigated experimentally. The high sensitivity of the oscillator characteristics to the change of the optical intensity affecting the semiconductor diode structure has been shown. It is suggested to use this mode for the creation of optoelectronic microwave systems with the controlled amplitude and phase of the output signal and for the high-accuracy indication of optical radiation.

Keywords — optical control, synchronization, semiconductor microwave oscillator, Gunn diode.

1. Introduction

At present considerable attention is paid to the researches, devoted to the development of optically controlled microwave semiconductor elements on the basis of bipolar and field transistors, IMPATT and TRAPATT diodes, Gunn diodes [1–3].

A lot of publications are devoted to the investigations of the performance of semiconductor microwave oscillators in the lock mode under the influence of optical radiation [4–6]. Circuits for frequency stability increase, systems with controlled amplitude and phase of output signal, required for example for phased array, were developed on the basis of these oscillators [6, 7].

Despite the fact that the optical power level, used for control of microwave semiconductor devices, is low, and the range of the fundamental frequency and power tuning is not more than several percent, the phase shift of output signal of the locked oscillator can reach 180°. This allows us by selecting the optical power level to obtain the optimal value of the output signal or to obtain almost complete suppression of the signal and to increase significantly the sensitivity of optoelectronic schemes to the optical radiation.

In this work the synchronized oscillator on the Gunn diode with optical control in the comparison circuit operating in the coherent signals subtraction mode is investigated experimentally and theoretically.

2. Analytical model

Consider the model of the single-circuit diode locked oscillator (Fig. 1) with the resistive active semiconductor element, IV-curve of which has a section of negative differential conductivity $G(U)$, which depends on the amplitude of AC voltage:

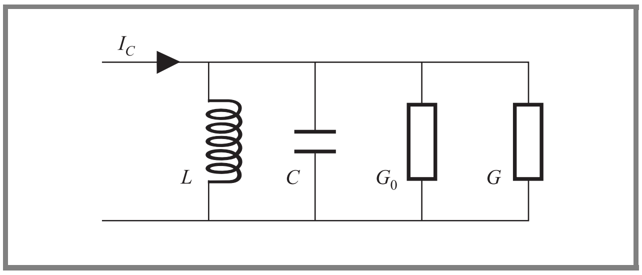

Fig. 1. Equivalent scheme of the single-circuit diode synchronized oscillator.

$$G(U) = -G_A + \alpha U^2 .$$

The gain-frequency characteristic $y(x)$ and the phase-frequency characteristic $\varphi(x)$ of such synchronized oscillator are described by the following equations [8]:

$$y\lfloor (y-1)^2 + x^2 \rfloor = F ,$$

$$\mathrm{tg}\varphi = \frac{x}{y-1} ,$$

and oscillations stability conditions in the steady-state mode are: $y > 0.5$ and $x^2 + (y-1)(3y-1) > 0$.

Variables describing frequency detuning, amplitude of oscillations and amplitude of an external influence are represented correspondingly:

$$x = \left(1 - \frac{\omega_0^2}{\omega^2}\right)\frac{q}{d_0}, \quad y = \frac{U^2}{U_0^2}, \quad F = \frac{q^2 E_C^2}{U_0^2} ,$$

where $q = \frac{G_0}{\alpha U_0^2}$, $d_0 = \frac{G_0}{\omega C}$, ω_0 and U_0 are the oscillations frequency of free-running oscillator and their amplitude, ω and $E_C = I_C/G_0$ are the frequency and amplitude of the external influence, C is the diode capacity, L is the inductance of diode holder, G_0 is the conductivity of load.

Since with the external synchronization in the steady-state mode the phase difference constancy between output signal of self-oscillator and synchrosignal is provided, then the investigation of the behaviour of the gain-frequency and phase-frequency characteristics of the signal in the load

G_L when subtraction of the output signal p_{out} of the self-oscillator and synchrosignal p_S is of interest.

The current in the load G_L can be represented as $I_L = I_{SL}\sin(\omega t+\alpha)+I_{out}\sin\left(\omega t+\beta-\varphi(x)\right)$, where I_{out} and I_{SL} are the amplitudes of currents, induced by the output signal of the synchronized oscillator on the load G_L and the synchrosignal on this load when conveying directly to the load G_L, $\varphi(x)$ is the phase difference which depends on the frequency detuning within the locking range, α and β are the initial phase difference.

The amplitudes of the currents I_{out} and I_{SL} in the load G_L, if load conduction equals oscillator's output conduction and internal conduction of the synchrosignal source, are defined from relations: $I_{out} = \sqrt{k_1 2P_{out}}G_L$, $I_{SL} = \sqrt{k_2 2P_{SL}G_L}$, where k_1 and k_2 are power-transfer coefficients of oscillator's output signal and synchrosignal to the common load defined by the power loss in transmission lines.

Under the coherent signals subtraction the phase ψ and the amplitude I_{L0} of the resulting current in the load $I_L = I_{L0}\sin(\omega t+\psi)$ are defined by expressions:

$$\psi = \mathrm{arctg}\left[\frac{I_{SL}\sin\alpha + I_{out}\sin(\beta-\varphi)}{I_{SL}\cos\alpha + I_{out}\cos(\beta-\varphi)}\right],$$

$$I_{L0} = \sqrt{I_{SL}^2 + I_{out}^2 + 2I_{SL}I_{out}\cos(\beta-\varphi-\alpha)}.$$

If amplitudes of currents I_{out} and I_{SL} are equal, and phase condition $\beta-\alpha-\varphi=\pi$ is fulfilled, almost complete suppression of the signal I_L is possible.

In the locking range the phase difference φ between oscillator's output signal and synchrosignal can vary from $-\pi/2$ to $\pi/2$. This allows us to achieve the antiphasing signals being added during the changing of frequency detuning x.

The power accepted in the load G_L is computed by formula: $P_L = I_{L0}^2/2G_L$.

The influence of optical radiation with quantum energy larger then the forbidden gap results in increasing the free charge carrier concentration in the semiconductor by the value of

$$\Delta n = \frac{\beta(1-R)IS_0\tau\alpha\left[\frac{\left[\alpha L_0^2+S_p\tau\right]}{(L_0+S_p\tau)}L_0\left(1-e^{-\delta}\right) - \frac{1-e^{-\alpha d}}{\alpha}\right]}{hv\left(\alpha^2L_0^2-1\right)d}$$

taking into consideration the surface recombination [9].

If an oscillator is the Gunn oscillator then the free charge carrier concentration change in semiconductor results in changing the negative differential conduction and capacity of Gunn diode [10]:

$$G_A = G_{A0}\frac{n_0+\Delta n(I)}{n_0},$$

$$C(I) = S\sqrt{\frac{q\left(n_0+\Delta n(I)\right)\varepsilon\varepsilon_0}{2U_d}},$$

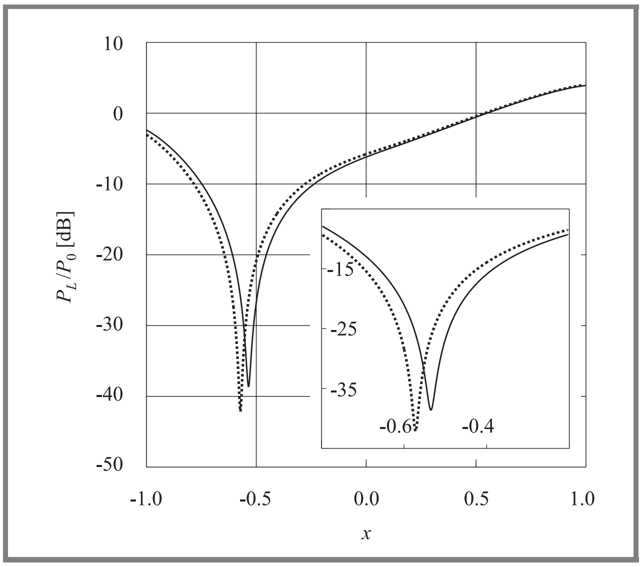

Fig. 2. The power-frequency characteristics of signal in the load.

where n_0 is the donor concentration, S is the diode area, U_d is the domain voltage.

The results of computation of synchronized Gunn-diode oscillator (SGDO) power-frequency characteristics at the constant synchrosignal power are shown in Fig. 2 (full curve). Computations show that the influence of the optical radiation of small intensity of 100 W/cm^2 results in changing the least value position on power-frequency characteristics (Fig. 2, dotted curve) and under the constant synchrosignal frequency – in considerable (up to 30 dB) changing the output power in the oscillator load (Fig. 3).

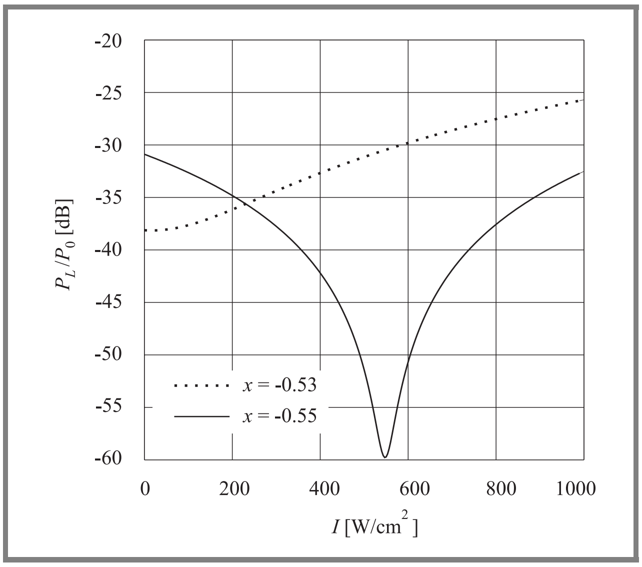

Fig. 3. The dependence of output signal from the optical intensity.

The phase-frequency characteristics $\psi(x)$ of the signal in the load G_L are shown in Fig. 4. On these characteristics at a point of minimum of power-frequency characteristics the

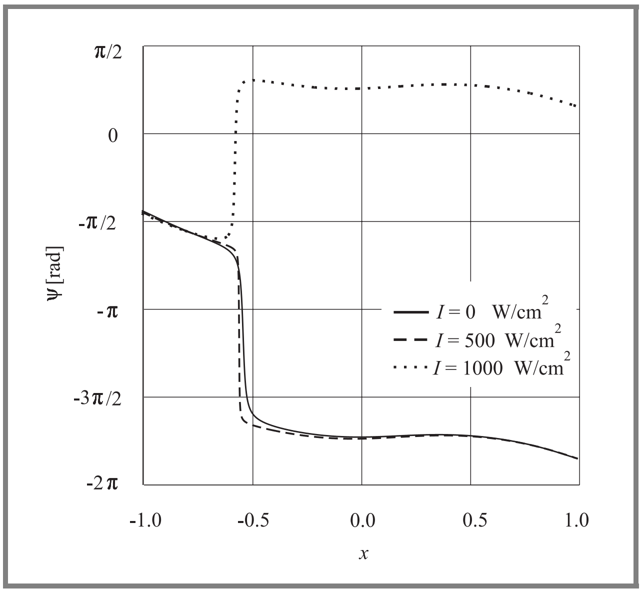

Fig. 4. The phase-frequency characteristics of signal in the load.

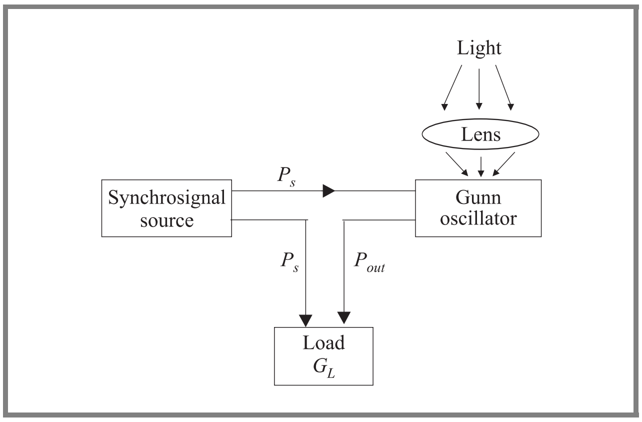

Fig. 5. The experimental setup.

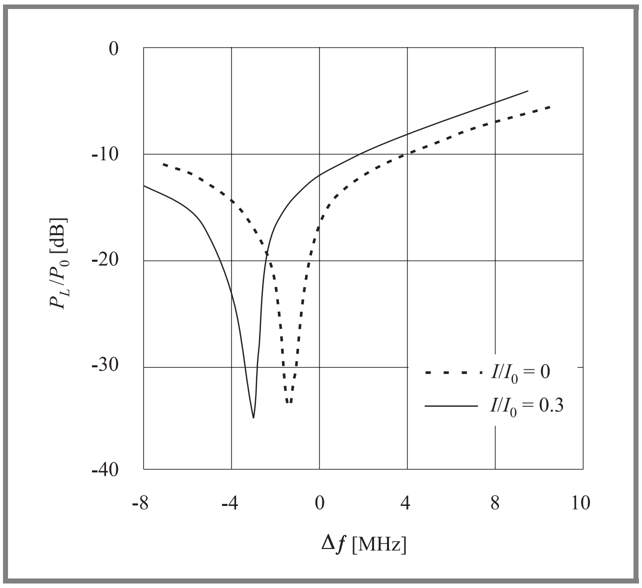

Fig. 6. The experimental power-frequency characteristics of the synchronized Gunn oscillator.

abrupt output signal phase ψ change up to π is observed. At the same time the slope of phase-frequency characteristic at a point of minimum of power-frequency characteristics under the influence of optical radiation can change its sign (Fig. 4, dotted curve).

The analysis of the obtained results shows that on the basis of the semiconductor oscillator synchronized by an external signal the microwave system realizing sufficiently great (up to 30 dB) levels of output signal change under the influence of optical radiation can be developed.

3. Experimental results

For the experimental investigations the setup shown in Fig. 5 was used. The semiconductor microwave oscillator of 3-centimeters region with Gunn diode 3A703 as active element was investigated. As a source of optical radiation the He-Ne laser was used. In one of the arms of circuit the synchrosignal source (microwave oscillator G4-83) was placed. In the other arm the Gunn oscillator was placed. At the output of the circuit the synchrosignal and Gunn oscillator output signal were summarized on the common load. The resultant signal was observed on the spectrum analyzer C4-27 and on the power meter M3-51.

By adjusting of Gunn diode bias, power level and frequency of synchrosignal and changing of the elements parameters the mode of coherent subtraction of both signals on common load has been implemented. While synchrosignal frequency change within the locking range the output power change up to 40 dB was observed.

The results of measurements of the dependence of the first harmonic power P_L/P_0 of the signal at the output of the bridge circuit in the load when oscillator operates in the locking mode on the synchrosignal frequency (power frequency characteristic) with (solid curve) or without (dashed curve) an external optical radiation are shown in Fig. 6.

It follows from these results that at a point of minimum of power-frequency characteristic the scheme under investigation has extremely high sensitivity (about 20 dB/MHz) to the change of the Gunn oscillator fundamental frequency. Therefore the influence of optical radiation of 100 W/cm^2, which results in the insignificant changes of frequency (about 1–3 MHz) and power (about 0.01–0.1 mW) of Gunn diode output signal, results in changing the least value position on power-frequency characteristics (Fig. 6, solid curve). With the constant synchrosignal frequency the influence of optical radiation results in significant (up to 30 dB) change of the synchronized oscillator output power in the load (Fig. 7). The dependencies of the first harmonic power P_L/P_0 of the SGDO output signal on the reduced optical intensity I at the constant detun-

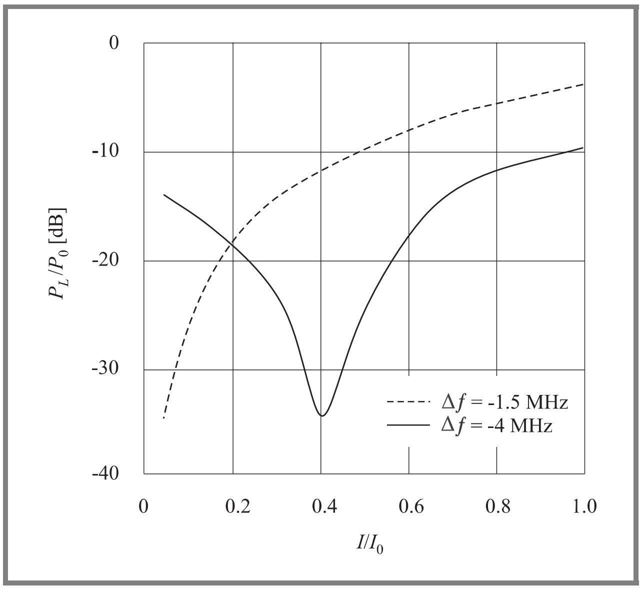

Fig. 7. Experimental dependencies of the SGDO output power on the intensity of the optical radiation.

ing Δf are shown in Fig. 7. By selecting detuning Δf both monotonous and non-monotone dependencies $P_L/P_0(I)$ can be obtained.

4. Computer simulation

For the description of the multicircuit SGDO in the bridge circuit in the mode of the coherent subtraction of the synchrosignal and the synchronized oscillator output signal on common load it is suggested to use the equivalent scheme shown in Fig. 8 [11].

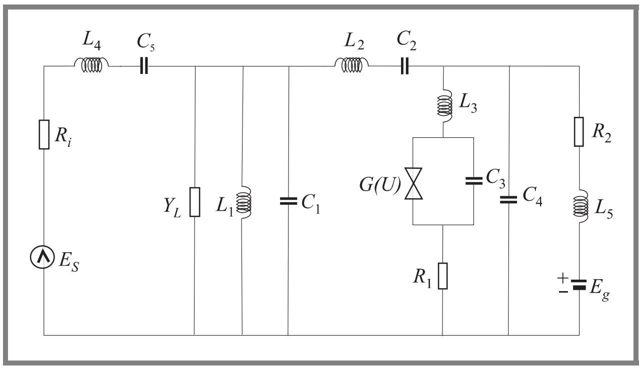

Fig. 8. The equivalent scheme of the SGDO.

Elements of this scheme simulate semiconductor structure of Gunn diode as connected in parallel capacity C_3, active nonlinear conduction $G(U)$ that is determined from IV-characteristic of the diode [11] and resistance R_1 connected in series; elements of diode body L_3 ,C_4, microwave circuit of diode presented as in-parallel L_1C_1, and in-series L_2C_2, circuits, equivalent conduction of load on the output of bridge scheme Y_L, Gunn diode feed circuit consisting of voltage source E_g, choke L_5, and resistance R_2; microwave circuit of synchrosignal generator containing source of alternating signal E_S, resistance R_i and in-series circuit L_4C_5.

This equivalent scheme is described by the system of ten first-order differential equations based on the Kirchhoff laws. The influence of the optical illumination was simulated, as in the analytical model, by the dependence of the Gunn diode negative differential conductance and capacity on the optical intensity.

As a result of numerical solution of the differential equations system the dependence of the instantaneous current in the load G_L as a function of time $i_L(t)$ was determined. By the Fourier transform of the $i_L(t)$ the harmonic components of the current in the load were calculated, their amplitudes were determined, and the powers of the harmonics at the output of the SGDO were calculated: $P_{kL} = i_{kL}^2/2Y_L$, where i_{kL} – the amplitude of the harmonic components of the current in the load, k – the number of a harmonic.

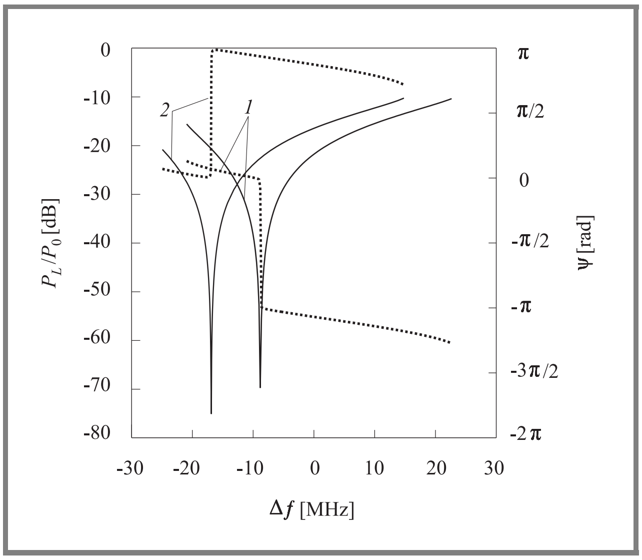

Fig. 9. Power-frequency (full curves) and phase-frequency (dotted curves) of the output signal first harmonic: *1*) $I = 0$, *2*) $I = 10^6$ W/m^2.

On the basis of the above mentioned model the calculations of the power-frequency characteristics of SGDO were carried out. The results of calculations of the SGDO power-frequency and phase-frequency characteristics at the constant synchrosignal power and the various values of optical intensity are shown in Fig. 9.

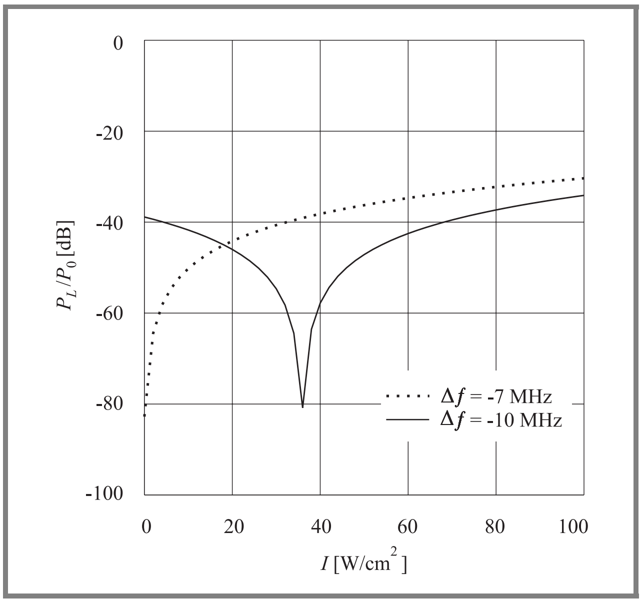

Fig. 10. The dependence of the output signal on the optical intensity.

The dependencies of the SGDO output power on the optical intensity for the various values of the detuning Δf are shown in Fig. 10. Depending on the detuning value the oscillator output power can be both monotone increasing (dotted curve) and having the minimum (solid curve). Here the changing of the output microwave signal power exceeded 40 dB. The steepness of the phase-frequency characteristic $\psi(x)$ at a point of minimum of the power-frequency characteristic is up to $\pi/$MHz.

5. Conclusion

In this work the influence of optical radiation on the performance of the synchronized microwave Gunn oscillator in the coherent signals subtraction mode has been described theoretically and investigated experimentally.

The experimental investigations and calculations show the high sensitivity of the oscillator characteristics to the change of the optical intensity affecting the semiconductor diode structure. This allows us to use the coherent signals subtraction mode in synchronized Gunn-diode oscillators for the creation of optoelectronic microwave systems with the controlled amplitude and phase of the output signal, for the high-accuracy indication of optical radiation and for the creation of the semiconductor microwave elements with extended functional possibilities.

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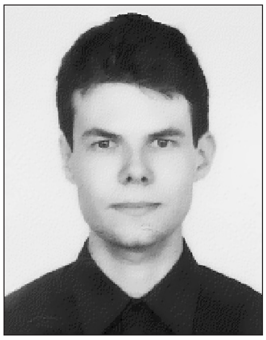

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