Izv. VUZ «AND», vol.10, № 3, 2002

NONLINEAR DYNAMICS OF MICROWAVE AND OPTICAL SEMICONDUCTOR OSCILLATORS

D.A. Usanov, Al.V. Skripal, An.V. Skripal, A.V. Abramov, A.A. Kletsov

The results of experimental and theoretical investigations of the nonlinear phenomena in microwave and optical semiconductor oscillators are represented. It is shown that one of the reasons of occurrence of various nonlinear phenomena in semiconductor devices of the microwave range is qualitative change of their voltage-current characteristics, in particular occurrence or disappearance of sections of negative differential resistance under the influence of high-power microwave radiation on semiconductor structures. The external optical feedback forming autodyne operating mode of semiconductor lasers acts as the priority mechanism of realization of their nonlinear operating mode in semiconductor laser structures.

Introduction

By now on the base of semiconductor devices the systems realizing various radio-engineering functions in the microwave and optical range have been created. One of the features of semiconductor devices is the dependence of their characteristics on the power level of the affecting signal [1,2]. As the result of such influence semiconductor devices can essentially change their operating mode.

In the microwave range the reason for such changes can be qualitative change of the current transport mechanism in the semiconductor structures and therefore the change of the shape of the voltage-current characteristics.

In semiconductor elements, which are the sources of optical radiation, one of the mechanism, which results in a great number of nonlinear phenomena, is the external optical feedback, which, in particular, forms the autodyne operating mode of semiconductor lasers [3]. Thereupon, theoretical and experimental investigations of the nonlinear dynamics of semiconductor devices in microwave and optical range under the influence of an external signal are actual ones.

Microwave semiconductor oscillators

When describing the properties of semiconductor devices in the microwave region it is often considered possible to use their stationary or small-signal characteristics (voltage-current characteristic, impedance). Such approach allows us to successfully construct microwave systems of various types on the base of semiconductor devices. At

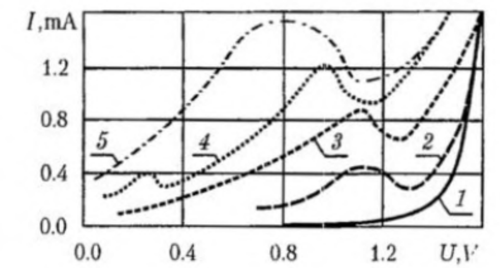

Fig. 1. The voltage-current characteristics of *p-i-n*-diode 2A534A. *P*, mW: *1* - 0; *2* - 40; *3* - 150; *4* - 420; *5* - 680

the same time it is clear that with the increase of the power level of an affecting signal the considerable change of the semiconductor devices properties is possible.

The influence of the strong electromagnetic radiation on the semiconductor devices operating mode has dictated the necessity of creation of the microwave delimiters and in particular on the base of *p-i-n*-diodes. I.e. *p-i-n*-diodes in such devices are under the influence of the high-level microwave power.

As the result of the carried out investigations it was determined that under the certain levels of affecting microwave power the stick-slip change of the rectified current and the stick-slip change of the output spectrum could take place in *p-i-n*-diodes [4, 5], one or more sections with negative differential resistance on the *p-i-n*-diodes voltage-current characteristics could appear. The voltage-current characteristics of *p-i-n*-diode 2A534A under the different levels of input power are shown in Fig. 1. So in the quasiactive delimiter on the base of *p-i-n*-diodes 2A522A and 2A534A with the increase of the input power up to 300 mW the decrease by 5-6 dB of the spectrum component f_0, which is the frequency of the input signal (800 MHz), and the rising of the subharmonic at the 400 MHz were observed (Fig. 2, *a*).

At the input power of the 700 mW the spectrum component $f_0/4$ arose (Fig. 2, *b*), at the 1000 mW the noise spectrum was observed, at the 1100 mW the spectrum component $f_0/3$ arose (Fig. 2, *c*), at the 1800 the spectrum component $f_0/6$ arose (Fig. 2, *d*). The initiation of those spectrum components was accompanied by the stick-slip change of power with hysteresis character. The influence of additional signal with the frequency differing from the basic signal frequency on the *p-i-n*-diode can result in the considerable decrease of the basic signal power at which subharmonics appear. The presentation of the equivalent scheme of *p-i-n*-diode as the oscillatory circuit allows us to describe the subharmonics initiation and hysteresis, but not in so complicated sequence as it was observed in the experiment. It was found that the influence of microwave radiation on *p-i-n*-diodes can result in arising on their voltage-current characteristics of one or more sections with negative differential resistance (NDR) of *N*-type and consequently in initiation of generation of high-frequency oscillations and modulation of output microwave signal by the relatively low-frequency oscillations which frequency and form in turn depend on the input power level. The theoretical description of that effect is

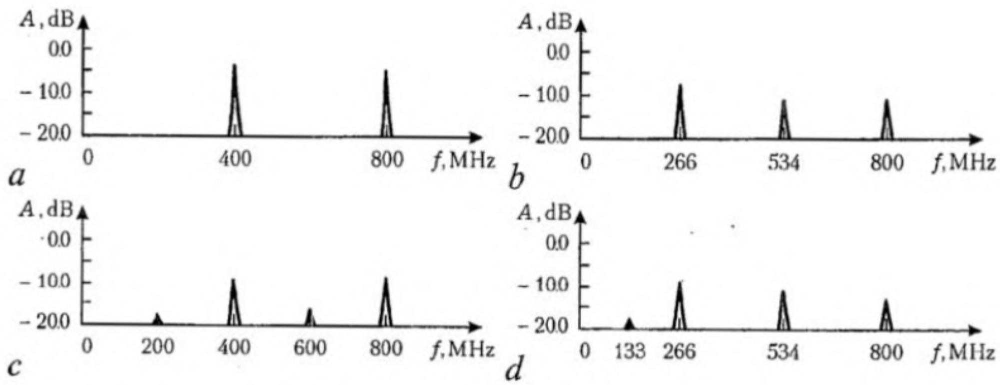

Fig. 2. The spectrograms of the output signal of the microwave delimiter on the base of *p-i-n*-diodes

possible with taking the dependence of diode impedance on the input power level, the charge carriers heating and detection effect into consideration in the physical model [6].

The phenomenon of harmonics initiation under the influence of the microwave signal on the semiconductor element was investigated thoroughly. To prevent the influence of the higher harmonics on the characteristics of microwave delimiters on the base of *p-i-n*-diodes the low-pass filters were used. At the same time the arising subharmonics in the wide-band waveguide systems can propagate and therefore influence on the output parameters of a device, in particular, they can increase the power level which leaks through the power delimiter. Carried out experimental investigations show, that introduction into the delimiter scheme of the high-pass filter, which cuts off subharmonics, allows us to reduce essentially the level of microwave power leak [7].

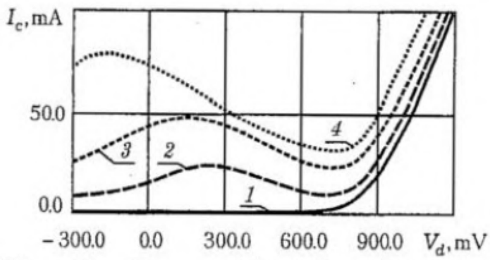

Fig. 3. The experimental voltage-current characteristics of a microwave diode. *P*, mW: *1* - 0; *2* -100; 3 - 300; *4* - 600

Experimental investigations and theoretical description show, that the influence of high-power microwave field effects dramatically on the current transport mechanism in the structures on the base of *p-n*-junction which results in the qualitative change of the shape of the voltage-current characteristics.

The experimental voltage-current characteristics of the microwave diode for the different power levels of input signal are shown in Fig. 3. As it follows from the experimental results with the increase of the input power up to 150 mW the section of NDR of *N*-type appears on the diodes voltage-current characteristics. The magnitude of the NDR increases with the growth of the input power in the range from 150 to 500 mW. At the input power of 500 mW NDR reaches -20 Ω, and in the feed circuit the low-frequency oscillations of ~200 kHz are initiated [8, 9].

Thus the essential result is: the structures with *p-n*-junction, which are incapable of generating or gaining oscillations without external electromagnetic radiation, under the influence of electromagnetic radiation become capable of that. At that the frequency and the amplitude of the generated signal depend on the affecting signal parameters.

The degree of generality of the obtained results is of interest. Do the similar phenomena appear in semiconductor structures of different types?

Another example when the structure with *p-n*-junction is under the influence of powerful external signal is microwave multipliers. The desire to obtain at the output of the multiplied signal of maximum power results in the increase of the input signal power. Carried out theoretical and experimental investigations have shown, that in multipliers the shape of the voltage-current characteristic qualitatively changes and the section with NDR appears. The change of the voltage-current characteristic shape under the influence of powerful microwave signal allows us to explain the maximum of the multiplying efficiency [10].

One of the best-investigated semiconductor microwave devices is the tunnel diode. There are theoretical investigations of nonlinear dynamics of devices based on tunnel diodes. One of the approximation assumed when modeling the operation of devices on the base of tunnel diodes is that tunnel diode voltage-current characteristic have the section of NDR of *N*-type which remains unchanged with the increase of the affected microwave power.

As the result of carried out experimental investigations it was determined that on the contrary to the situation described above and typical for *p-i-n*-diodes and diodes with non-degenerate *p-n*-junction such influence on the tunnel diode can result in the change of its voltage-current characteristic from *N*-type to exponential one which is typical for non-degenerate *p-n*-junction. The experimental voltage-current characteristics of a tunnel diode at the different values of microwave power are shown in Fig. 4 [11].

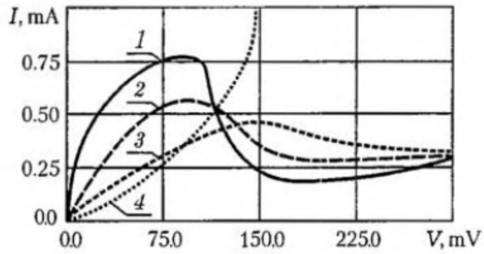

Fig. 4. The experimental voltage-current characteristics of a tunnel diode. *P*, mW: *1* - 0; *2* - 0.05; *3* - 0.2; *4* - 2.2

In the case of using of the tunnel diode as the active element of a microwave oscillator the consequence of the increase of the external signal power is the decreasing of the generating power and subsequent oscillations failure. At that the restoration of the oscillation mode is observed at essentially smaller external microwave power, i.e. the dependence of the power generated by the tunnel diode on the power of the external microwave signal has the hysteresis character [12].

As well known *N*-shape of the tunnel diode voltage-current characteristic is related to the fact that *p-n*-junction is formed as a result of a contact of two degenerated semiconductors. Therefore, the disappearance of the section of NDR, which is observed under the influence of microwave radiation, can mean the removal of degeneration in *p*- and *n*-regions of *p-n*-junction. The theoretical description of the phenomenon of changing the shape of the tunnel diode voltage-current characteristics under the influence of high-power microwave signal [13] has shown that the disappearance of the section of NDR is related to the decrease of the tunnel component and to the abrupt increase of the diffusion component of the full current because of the free charge carriers heating and appearing the detected signal. The description of the model of the oscillator on the tunnel diode under the influence of an external microwave signal because of the free charge carriers heating and appearing the detected signal is given in [14].

In [15] the experimentally found mode of initiation of NDR and switching in tunnel diode under the influence of an external microwave signal [16] in the case when the bias without microwave signal is essentially less than the peak value is described.

At present to obtain the maximum radiation power in the short-wave part of the microwave range one uses IMPATT-diodes as the active elements of oscillators [17]. In the large-signal mode the effects related to the nonlinear dependence of the IMPATT-diode parameters on the amplitude of an affecting signal are arose. One of them is the effect of changing the IMPATT-diode direct current rating because of the detection process on the diode nonlinear resistance [1].

The results of experimental investigations of the character of changes in voltage-current characteristics of IMPATT-diodes as the dependence on affecting microwave power level were presented in [18]. With the increase of the power level of the microwave signal of frequency 2500 MHz the gradual deformation of the IMPATT-diode voltage-current characteristic which is characterized by the increase of current both at the forward and reversed bias was observed. Further (up to 5.0 W) increase of the external microwave power resulted in the initiation of the section of the abrupt current growth on the voltage-current characteristic (see the arrow in Fig. 5) at the negative bias far away from the avalanche breakdown voltage in the region of thermal current. The steepness of that section and the current surge increased with the growth of the external microwave power. On the left and the right sides from that section the regions of *N*-type NDR appeared (curve 2 in Fig. 5). When the microwave exposure was switched off, the diode voltage-current characteristic took the initial form, which is typical for IMPATT-diodes without the external microwave signal (curve 1 in Fig. 5).

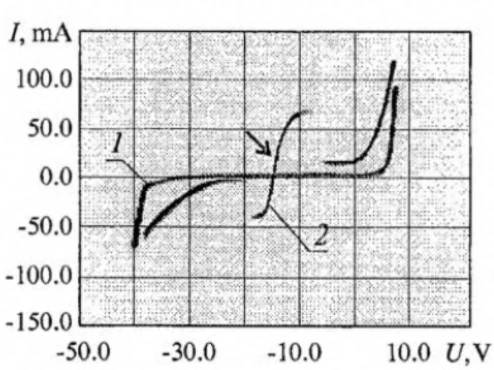

Fig. 5. The experimental voltage-current characteristic of an IMPATT-diode. P, W: *1* - 0; *2* - 5.0

It was experimentally determined that the location of these sections of current surge and NDR on the IMPATT-diode voltage-current characteristic depends essentially on the IMPATT-diode microwave circuit parameters. When the input load of the IMPATT-diode changed as the result of the short-circuiting plug shift on ~0.2 λ (λ is the wavelength of the microwave signal) at the constant power of the input signal of 5.0 W the monotonous shift of the additional section of the abrupt current growth was observed. If with such shift the impedance matching of the coaxial line and the IMPATT-diode takes place then the power of the external microwave signal accepted by the semiconductor structure increases and the sections of NDR of N-type appear.

At present the *GaAs* MESFETs are widely used for gain of microwave oscillations. Therefore to discover the specificity of practically used devices with *GaAs* MESFETs under the influence of high-power microwave signal is of interest when the nonlinear properties of transistor become essential ones.

The mode of subharmonic oscillations is the intermediate state before the chaos state, for subharmonics to appear the presence of nonlinear capacity, parallel to nonlinear resistivity, is essential. Since the nonlinear capacities and diodes model the area under the transistor gate, one may suppose that when the microwave signal of rather high power is applied to the transistor input, the subharmonics can arise in its output spectrum.

To find the subharmonics in output spectrum experimentally the amplifier of medium power on the base of *GaAs* MESFET was investigated. The length and the width of the gate and the thickness of the channel, when the charge carrier concentration equals to $(1\div2)\cdot10^{17}$ cm^{-3}, is 1 μm, 300 μm and 0.3 μm correspondingly. The transistor was mounted in the microstrip scheme. The signal of frequency of f_0=14 GHz from the microwave oscillator G4-111 through the variable attenuator, power amplifier, low-pass filter with the cutoff frequency f_c<f_0 was applied to the wattmeter M3-54 and to the spectrum analyzer S4-60.

As the result of the experimental investigations it was determined that with the increasing the power of the input signal up to 140 mW the spectrum components with frequencies divisible to $f_0/9$ appeared. The spectrogram of the output signal is shown in Fig. 6.

The theoretical description of the conditions of subharmonics arising in the output spectrum of the medium-power *GaAs* MESFET with the gate of 1×300 μm, which operated in the amplifier mode, was carried out by means of numerical simulation with the use of equivalent scheme, the nonlinear elements parameters of which depended both on bias magnitude and on input microwave power level [19-21].

As the result of numerical solution of the system of differential equations, describing the equivalent scheme, the dependence of instantaneous values of the current in the load on time was determined. The phase-plane portrait of this system in the mode with stable subharmonic oscillations of current in the load and the spectrogram of the output signal at the input signal of 190 mW are represented in Fig. 7. and 6.

During the experimental researches it was determined that decrease of inductance values of input and load circuits leads to the disappearance of subharmonic oscillations of frequencies divisible to the $f_0/9$ and the occurrence of subharmonic with frequency equal to $f_0/2$ in the analyzed dynamical system [19].

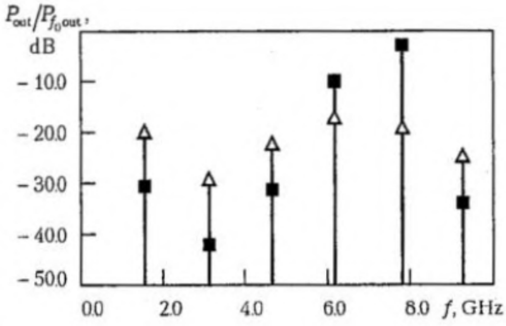

Fig. 6. The spectrogram of the output signal of the *GaAs* MESFET amplifier

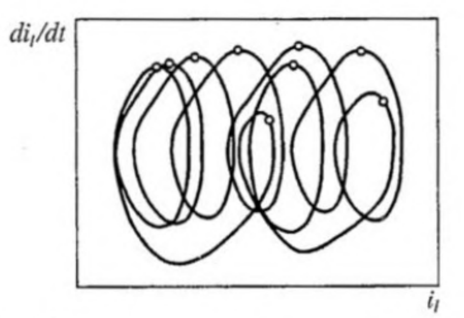

Fig. 7. The phase-plane portrait of the *GaAs* MESFET amplifier

Thus as a result of researches it was experimentally determined and theoretically proved the possibility of subharmonic existence in the output signal spectrum of medium-power microwave amplifier on GaAs MESFET. The intervals of feed voltage and input signal power at which the arising of subharmonics is possible were determined. These subharmonics are characterized by large whole number equal to the ratio of input signal frequency and subharmonic frequency. It is shown that on the going out of these intervals, including the case when power exceeds the certain value, subharmonics in the spectrum disappear. The latter indicates that with change of external signal level and, as a consequence, direct current rating, the nonlinear characteristics of transistor stipulating for bifurcation peculiarities change.

Optical semiconductor autodynes

At present semiconductor laser diodes are an integral part of data-measuring fibre-optical systems. One of the nonlinear effects widely used in practice in such systems is the effect of autodyne detection in active area of the semiconductor laser structure, arising due to influence of the optical signal formed by an external optical feedback on the laser diode. The reflected wave leads to the change of the charge carrier concentration in the active medium and to the change of the optical generation frequency [3]. Significant interest to effect of autodyne detection in semiconductor lasers is caused by an opportunity of creation on their basis of simple measuring gauges with high sensitivity to the reflected signal [21-28].

The semiconductor laser with external optical feedback can be described by the composite resonator model [29]. Theoretical analysis is based on the solving of the field equation for a complex electric field and the rate equation for density of charge carriers [30, 31].

The system consisting of the semiconductor laser and an external reflector combines functions of the oscillator and the electromagnetic wave phase detector in one device. For researched objects with small reflectance (not more than 1%) the functions of the oscillator and of the detector are realized practically independent from each other. With growth of a feedback level their mutual influence grows, in particular, the form of autodyne signal begins to differ from the form of interference signal formed by the same movement of a reflector in interference system with decoupling from a source of radiation. At the same time the level of a feedback, stationary phase, character of movement of an external reflector influence essentially the form of autodyne signal [32-34].

In approximation of a stationary field the expression for linearized normed power of electric field P/P_0 can be represented as [35]:

$$P/P_0 = \cos(\omega\tau),$$

and the phase equation for stationary wave phase in the external resonator for the laser with a feedback can be represented as

$$\varphi = \varphi_0 - C\sin(\varphi + \mathrm{arctg}(\alpha)),$$

where $\varphi_0 = \omega_0\tau$ is stationary wave phase for the laser without feedback, $C = \tau z(1+\alpha^2)^{1/2}$ is the parameter of an external optical feedback, ω_0 is the resonance frequency of the natural resonator of the laser diode without a feedback on a threshold of generation, α is the factor of widening of generation line, τ is the roundtrip time of the external resonator, z is the factor of external optical feedback.

For object vibrating under the sine wave law the function of stationary wave phase in the external resonator for the laser with a feedback $\varphi(t) = \omega(t)\tau(t)$ was set as:

$$\varphi(t) = \varphi_{0F} + \varphi_{0A}\sin(\Omega t),$$

where φ_{0F} is the value of stationary phase at the fixed distance L to reflector, φ_{0A} is the amplitude of change of phase, Ω is the frequency of vibrations of the reflector.

In Fig. 8 the dependences of average normed power P/P_0 on time t are represented. They describe movement of external reflector with frequency of mechanical oscillations $\Omega=1/T$ (T is the period of oscillations of the reflector) and amplitude $\xi=1$ μm for the laser with wave length of $\lambda=1.3$ μm where the specified parameters are related to amplitude of change of phase as:

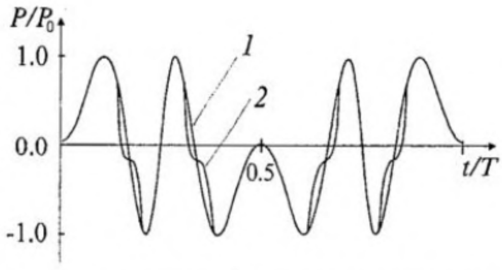

Fig. 8. Dependences of the average normed power P/P_0 on time t at the vibrations of an external reflector described by parameters $\varphi_{0F}=\pi/2$, $\varphi_{0A}=2\pi$, $L=1.5$ sm, for two values of feedback parameter: *1* - $C=0.09$, *2* - $C=0.2$

$$\varphi_{0A} = 4\pi\xi/\lambda.$$

As follows from Fig. 8, with growth of feedback parameter C the deviation from the initial form of autodyne signal appears to be different on various sections of dependence $P(t)$. At the same time it is possible to single out sections with abrupt changes of inclination angle of autodyne signal which as calculations have shown correspond to occurrence of a mode of continuous relaxational oscillations [3].

In Fig. 9 the results of calculation of dependence of autodyne signal on time t normed on the period T and phase-plane portraits of autodyne system signal are represented. Hear $C=0.8$, $\alpha=5$, the amplitude of vibration $\xi=0.2\lambda$, stationary phase $\omega_0\tau_0=1.6\pi$ (Fig. 9, *a*), $\omega_0\tau_0=0.6\pi$ (Fig. 9, *b*). As follows from Fig. 9, *a*, *b* the degree of the deviation of the form of autodyne signal from harmonic law at the fixed values of

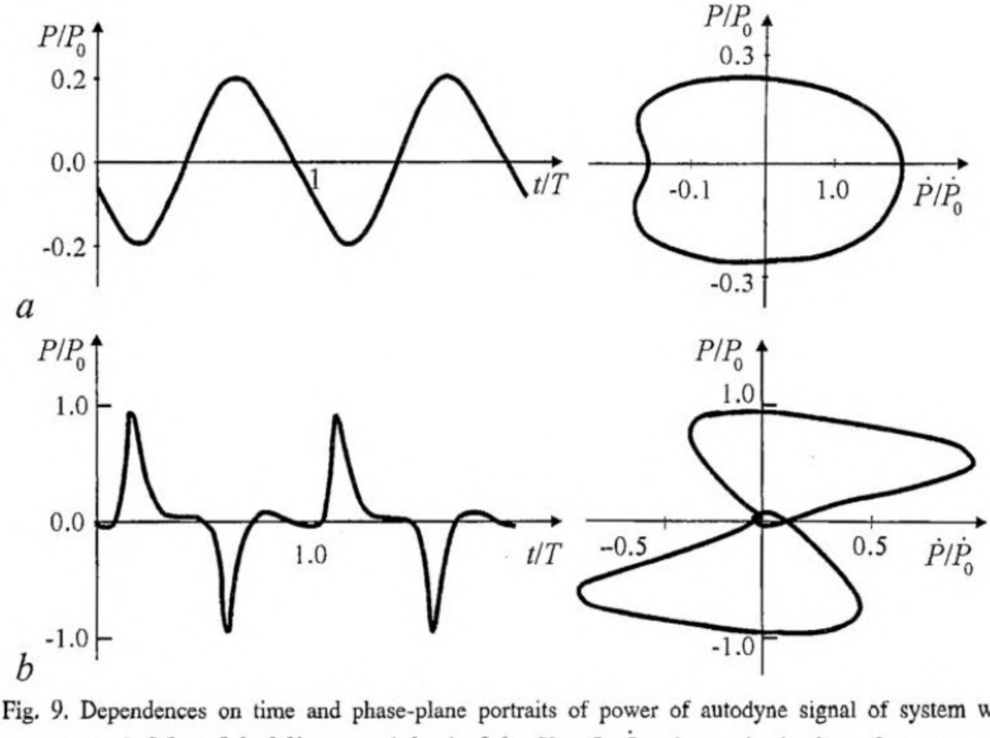

Fig. 9. Dependences on time and phase-plane portraits of power of autodyne signal of system with parameters: $C=0.8$, $\alpha=5$, $\xi=0.2\lambda$, φ_0: *a* - 1.6π, *b* - 0.6π. Here P_0, $\dot{P}_0$ - the maximal values of output power and it's derivative in a range of values of φ_0 from 0 up to 2π

feedback parameters and values of vibration amplitudes is defined by the magnitude of stationary phase $\omega_0\tau_0$.

Experimental researches of structure of the phase-plane portrait of autodyne signal were carried out with the help of setup the scheme of which is represented in Fig. 10.

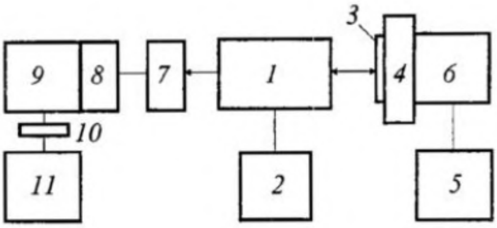

Fig. 10. The scheme of experimental setup: *1* - the semiconductor laser, *2* - the source of current, *3* - the reflector, *4* - the piezoceramics, *5* - the generator of sound oscillations, *6* - the micrometric mechanism, *7* - the photodetector, *8* - the filter of alternative signal, *9* - the amplifier, *10* - the analog-digital converter, *11* - the computer

Radiation of the semiconductor laser 1 (ILNP-206), fed by the DC source 2, was directed on the reflector 3 fixed on piezoceramics 4, vibrations of which were stimulated by the generator of sound oscillations 5. The opportunity of moving of vibrating reflector was provided with the micrometric mechanism 6. The part of the reflected radiation returned to the resonator of the semiconductor laser, output power change of which was registered by the photodetector 7. The signal from the photodetector went through the amplifier 9 containing the filter of an alternative signal 8, to an input of the analog-digital converter 10 of computer 11.

In Fig. 11 the measurement results of the signal of autodyne system are represented at various values of stationary phase. As follows from Fig. 9 to Fig. 11, theoretical and experimental curves of autodyne signal and the phase-plane portraits are in good correspondence. However at the certain distances up to the external reflector on the phase-plane portraits represented in Fig. 11, obtained experimentally, the occurrence of noise component of autodyne signal was observed. At the same time a degree of noise blurring of phase trajectory is various for its various sections. It is related to the fact that at the certain values of stationary phase the mode of generation of the semiconductor laser can change qualitatively starting from certain value of amplitudes of vibrations of reflector [35].

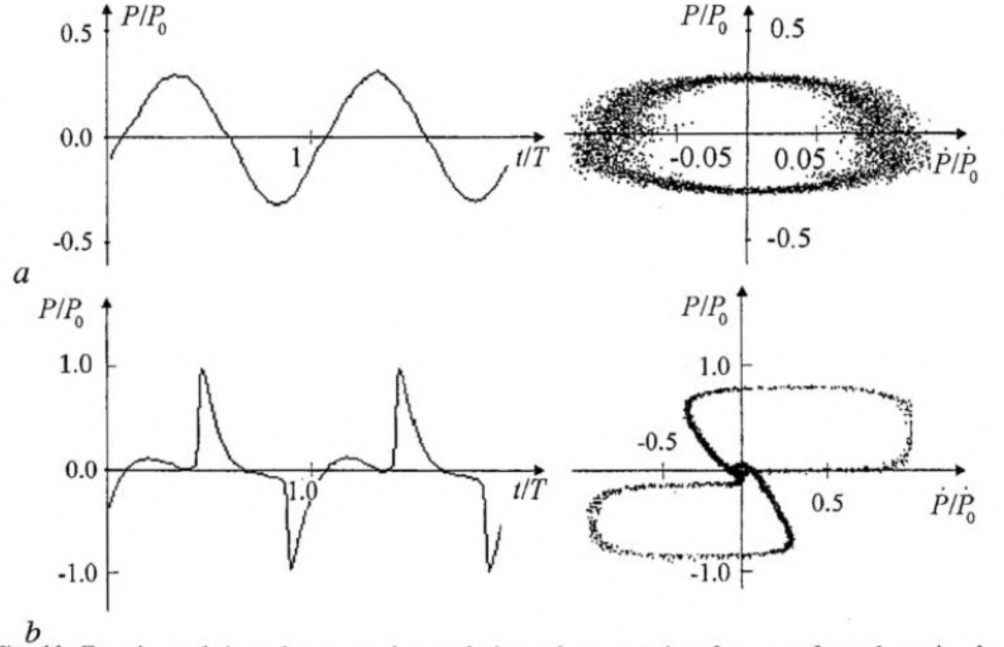

Fig. 11. Experimental dependences on time and phase-plane portraits of power of autodyne signal at various values of stationary phase φ_0: *a* - 1.5 π, *b* - 0.5 π

It is proved by the phase-plane portraits of output power P at movement of reflector of laser radiation for various values of a current through the laser diode that are shown in Fig. 12.

As follows from Fig. 12, increase of a current through the laser diode results in consecutive change of the phase trajectories describing the transition of the laser from the mode of spontaneous radiation (Fig. 12, *a*) in the laser mode (Fig. 12, *b*), then in the mode of unstable generation (Fig. 12, *c*, *d*) and later in the mode with a high degree of nonlinearity of autodyne system signal. Distinctive feature of unstable generation mode of the semiconductor laser is not the blurring of trajectories on the whole phase-plane portrait, but only their blurring on its separate sections (Fig. 12, *c*, *d*). Such behavior of

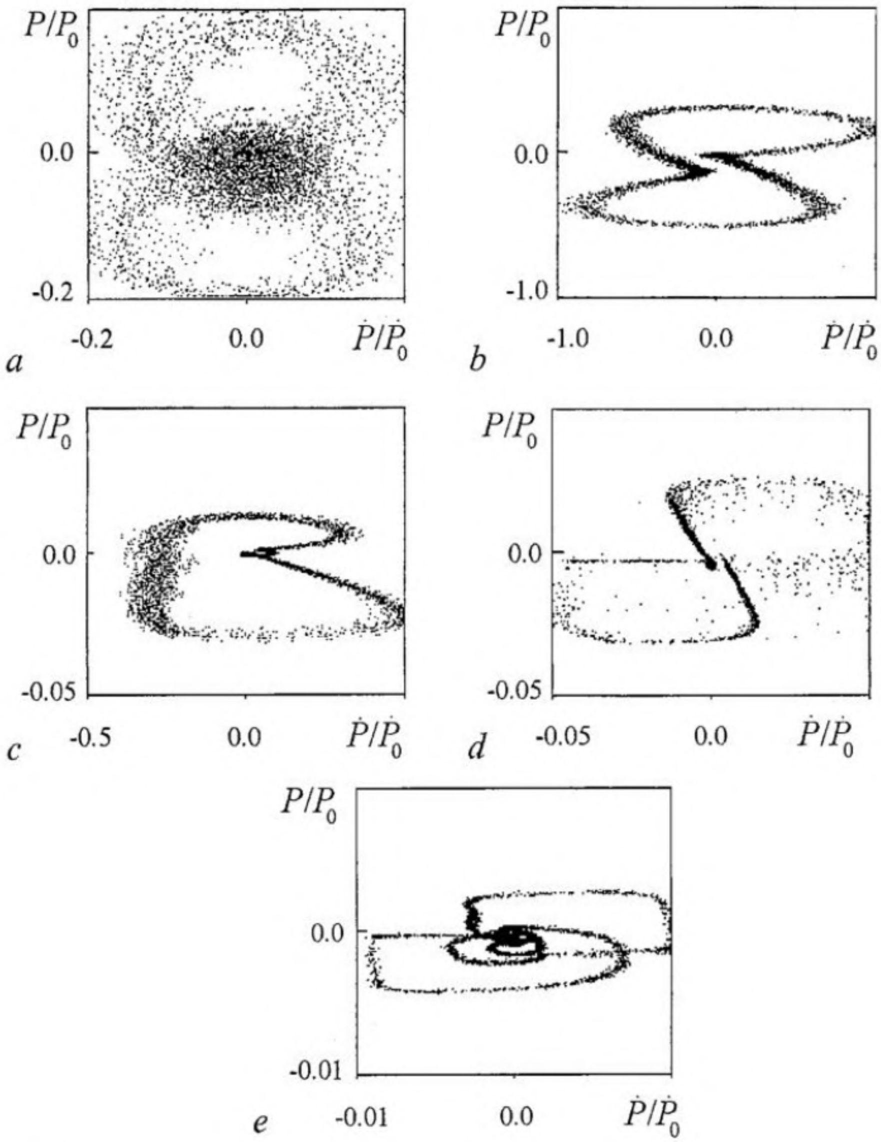

Fig. 12. Phase-plane portraits of output power of the semiconductor laser at movement of a reflector of laser radiation for various values direct currents of the laser diode: *a* - 58 mA, *b* - 63 mA, *c* - 68 mA, *d* - 70 mA, *e* - 78 mA

phase trajectories is related to strong dependence of operating mode of the semiconductor laser on position of the external reflector.

Conclusion

Thus, the results of experimental and theoretical researches given in the present work show that one of the reasons of occurrence of a various nonlinear phenomena in semiconductor devices of the microwave range is qualitative change of their voltage-current characteristics, in particular occurrence or disappearance of sections of negative differential resistance under the influence of high-power microwave radiation on semiconductor structures.

It is shown that in semiconductor laser structures the external optical feedback forming autodyne mode of operation of semiconductor lasers acts as the priority mechanism of realization of their nonlinear operating mode.

The work was supported by the Program on Educational Ministry of Russian Federation.

References

1. *Usanov D.A., Skripal A.V.* Physics of semiconductor devices operation in microwave circuits. Saratov: Saratov University Publish., 1999. 376 pp.

2. *Petermann K.* Laser Diode Modulation and Noise. Kluwer Academic Press, Dordrecht, The Netherlands. 1988. 390 p.

3. *Kalinkin M.Yu., Usanov D.A., Skripal A.V.* Autodyne detection in semiconductor-laser-generated relaxation oscillation// Proc. SPIE. 2000. Vol. 4002 P. 176-179.

4. *Vinenko V.G., Krasovskij S.V., Usanov D.A.* Modulation of a target signal in microwave power limiters on p-i-n-diodes// Elektronnaja tekhnika. Ser. 1. 1987. Vol. 4. pp. 38-39.

5. *Dzehtser G.B., Nikolaev J.I., Orlov O.S.* To a question on interaction of the plane semiconductor diode with an electronic microwave field// Voprosi radioelektroniki. Ser. 6. Radioelektronnja tehknika. 1971. Part 3. P. 3-12.

6. *Usanov D.A., Skripal A.V., Ugrjumova N.V.* Occurrence of negative differential resistance in p-i-n-diode structures at influence of microwave radiation// Izvestija Vuzov. Electronica. 1997. № 3-4. P. 48-52.

7. *Usanov D.A.* The possible lines of investigation for the semiconductor microwave electronics device parameters improvement // Radiotekhnika. 1999. № 4. P.96-99.

8. *Usanov D.A., Skripal A.V., Ugrjumova N.V.* Occurrence of negative resistance in structures on a basis of p-n-junction in the microwave field// Fizika i Tekhnika Poluprovodnikov. 1998. V.32, № 11. pp. 1399-1402.

9. *Usanov D.A., Skripal A.V., Ugrjumova N.V.* Occurrence of negative differential resistance on volt-current characteristics of diode structures on a basis of p-n-junction at influence of microwave radiation of a high level of power// Radiotehknika i elektronica. 2000. V. 45, № 12. P. 1509-1513.

10. *Usanov D.A., Skripal A.V., Posadskij V.N., Ugrjumova N.V.* Efficiency of frequency multiplication with the help of semiconductor diodes in a strong microwave field// Thes. of VI International sience-tech. conf. «Electrodynamics and engineering of the microwave and short-wave radiation» Samara, 1999. Vol. VII. Part.2 (23). P. 148-149.

11. *Usanov D.A., Korotin B.N., Orlov V.E., Skripal A.V.* Removal of degeneration in p-and n-areas of p-n-junction with external microwave signal// Pis'ma v Zhurnal Tekhnicheskoi Fiziki. 1990. Vol. 16, Part. 8. P. 50-51.

12. *Usanov D.A., Orlov V.E., Korotin B.N., Skripal A.V.* Influence of an external microwave signal on the work of the microwave oscillator on the tunnel diode// Izvestija VUZOV. Radiophysics. 1991. Vol. 34, № 1. P. 81-85.

13. *Usanov D.A., Skripal A.V., Korotin B.N., Orlov V.E.* Influence of heating microwave field on a type of volt - current characteristic of the tunnel diode// Pis'ma v Zhurnal Tekhnicheskoi Fiziki. 1993. Vol.19, Part.7. P. 81-85.

14. *Skripal A.V., Usanov D.A., Abramov A.V.* Nonlinear dynamics of the oscillator on the tunnel diode at influence of an external microwave signal// Izvestija VUZOV. Prikladnaja nelineinaja dinamika. 2000. Vol.8, № 4. P. 66-73.

15. *Usanov D.A., Skripal A.V., Ugrjumova N.V., Venig S.B., Orlov V.E.* Occurence of a mode of negative differential resistance and switching in the tunnel diode under the influence of an external microwave signal// Fizika i Tekhnika Poluprovodnikov. 2000. Vol. 34, Part. 5. P. 567-571.

16. *Usanov D.A., Venig S.B., Orlov V.E.* The negative differential resistance of the tunnel diode induced by an external microwave signal// Pis'ma v Zhurnal Tekhnicheskoi Fiziki. 1999. Vol. 25, № 2. P. 39-42.

17. *Tager A.S., Vald-Perlov V.M.* IMPATT diodes and their application in the microwave engineering. M.: Sovetskoe Radio, 1968. 480 p.

18. *Usanov D.A., Skripal A.V., Kletsov A.A.* Effect of occurrence of N-type negative differential resistance areas on volt-current characteristics of IMPATT diodes in a strong microwave field// Materials of 11-th International conference «Microwave engineering and telecommunication technologies» Crimico, 2001. 10-14 September 2001. Sevastopol. P. 170-171.

19. *Skripal A.V., Usanov D.A., Tyajlov V.S., Vasilieva A.V.* Subharmonic Generation in GaAs FET Amplifier// Proc. 11 International Microwave Conf. MIKON-96. Poland. Warsaw. May 27-30.1996, Vol. 2. P. 450-453.

20. *Usanov D.A., Skripal A.V., Tjazhlov V.S., Vasileva A.V.* Occurrence of subharmonic components in a spectrum of output signal of GaAs MESFET// Works of 3rd All-Russia scientific and technical conferences with the international participation «Actual problems of solid-state electronics and microelectronics». Divnomorskoe 1996. 8-13 Sept. Taganrog RTU. P. 80-82.

21. *Skripal A.V., Usanov D.A., Vasileva A.V., Tjazhlov V.S.* Modelling of the microwave amplifiers on GaAs MESFET, operating in a nonlinear mode// Fizika volnovih processov i radiotehknicheskie sistemi. 1998. Vol.1. № 2-3. P. 30-32.

22. *Mocker H.W., Bjork P.E.* High accuracy laser Doppler velocimeter using stable long wavelength semiconductor lasers// Appl. Opt. 1989. Vol. 28. P. 4914-4919.

23. *Shinohara S., Mochizuki A., Yoshida H., Sumi M.* Laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode// Appl. Opt. 1986. Vol. 25. P. 1417-1419.

24. *Shimizu E.T.* Directional discrimination in the self-mixing type laser Doppler velocimeter// Appl. Opt. 1987. Vol. 26. P. 4541-4544.

25. *Jentik H.W., F.F. de Mul, Suichies H.E., Aarnoudse J.G., Greve J.* Small laser Doppler velocimeter based on the self-mixing effect in a diode laser// Appl. Opt. 1988. Vol. 27. P. 379-385.

26. *Koelink M.H., Weijers A.L., Greve J., Aarnoudse J.G., Graaf R., Dassel A.C.M.* Self-mixing laser Doppler velocimetry of liquid flow and of blood perfusion in tissue// Appl. Opt. 1992. Vol. 31. P. 5844-5851.

27. *Koelink M.H., Slot M., de Mul F.F.* Laser Doppler velocimeter based on the

self-mixing effect in a fiber-coupled semiconductor laser: theory// Appl. Opt. 1992. Vol. 31. P. 3401-3408.

28. *Margin A.V.* Doppler gauge of velocity based on injected laser// Technical Physics. 1994. Vol. 64, № 1. P. 184-189.

29. *Tromborg B., Osmundsen J.H., Olesen H.* Stability analysis for a semiconductor laser in an external cavity// IEEE J.Quantum Electron. 1984. Vol.20. P. 1023-1032.

30. *Olesen H., Osmundsen J.H., Tromborg B.* Nonlinear dynamics and spectral behavior for an external cavity laser// IEEE J. Quantum Electron. 1986. Vol. 22. P. 762-773.

31. *Osinski M., Buus J.* Linewidth broadening factor in semiconductor lasers (an overview)// IEEE.J. Quant. Electron. 1987. Vol. 23. P. 9-24.

32. *Kalinkin M.Yu., Usanov D.A., Skripal A.V.* Determination of mechanical vibration form of external reflector by response of autodyne interference system based on a semiconductor laser// Proc. SPIE. 1999. Vol. 3726. P. 49-51.

33. *Skripal A.V., Usanov D.A., Kalinkin M.Yu.* Determination of comlicated movment form of the object by the signal of autodyne detection of semiconductor laser// Technical Physics. 2000. Vol. 70. P. 125-129.

34. *Skripal A.V., Usanov D.A., Vagarin V.A. and Kalinkin M.Yu.* Autodyne detection in a semiconductor laser as the external reflector is moved// Technical Physics. 1999. Vol. 44. P. 66-68.

35. *Usanov D.A., Skripal A.V., Kalinkin M.Yu.* Formation of autodyne signal in the semiconductor laser at the movement of an external reflector// Izvestija VUZOV. Prikladnaja nelineinaja dinamika. 1998. Vol. 6, № 1. P. 3-9.

Saratov State University *Received 4.07.2002*

УДК 621.382

НЕЛИНЕЙНАЯ ДИНАМИКА ПОЛУПРОВОДНИКОВЫХ СВЧ И ОПТИЧЕСКИХ ГЕНЕРАТОРОВ

Д.А. Усанов, Ал.В. Скрипаль,
Ан.В. Скрипаль, А.В. Абрамов, А.А. Клецов

Приведены результаты экспериментальных и теоретических исследований нелинейных явлений в полупроводниковых СВЧ и оптических генераторах. Показано, что одной из причин появления разнообразного спектра нелинейных явлений в полупроводниковых устройствах СВЧ-диапазона является качественное изменение вида их вольтамперных характеристик, в частности, появление или исчезновение участков отрицательного дифференциального сопротивления при воздействии мощного микроволнового излучения на полупроводниковые структуры. В полупроводниковых лазерных структурах в качестве приоритетного механизма реализации нелинейного режима их работы выступает внешняя оптическая обратная связь, формирующая автодинный режим работы полупроводниковых лазеров.

Usanov Dmitry graduated from the Faculty of Physics of Saratov State University in 1965. Doctor of Science in Physics and Mathematics since 1989, Professor of Chair of Solid State Physics since 1990. Head of Chair of Solid State Physics of Saratov State University. He is the author of monographs, textbooks, more than 300 articles in the sphere of solid state electronics, physics of semiconductors and radiophysics. He is the author of more than 90 inventions and patents, the member of the IEEE, Honored Man of Science of Russian Federation (1998).

Skripal Alexander graduated from the Faculty of Physics of Saratov State University in 1976. Doctor of Science in Physics and Mathematics since 1998, Professor of Chair of Solid State Physics of Saratov State University since 1998. He is the author of more than 100 scientific publications, textbooks and inventions in the sphere of solid state electronics, semiconductor physics and radiowave control.

Skripal Anatoli graduated from the Faculty of Physics of Saratov State University in 1982. Doctor of Science in Physics and Mathematics since 1998, Professor of Chair of Solid State Physics of Saratov State University. He is the author of more than 100 scientific publications in the field of coherent optics, laser physics, physics of magnetic liquids, biophysics.

Abramov Anton graduated from the Faculty of Physics of Saratov State University in 2002. He is the post-graduate student of Chair of Solid State Physics of Saratov State University since 2002. He is the author of 15 scientific publications. His scientific interests include semiconductor physics, solid state electronics.

Kletsov Alexei graduated from the Faculty of Physics of Saratov State University in 1999. He is the post-graduate student of Chair of Solid State Physics of Saratov State University since 1999. He is the author of 5 scientific publications. His scientific interests include semiconductor physics, microwave electronics.