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NONLINEAR CHAOTIC DYNAMICS IN GUNN DEVICES

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Проведен аналитический обзор известных научных работ, посвященных нелинейной хаотической динамике СВЧ колебаний в полупроводниковых приборах на основе эффекта Ганна. Полученные результаты могут быть использованы при проектировании генераторов хаотических сигналов для систем телекоммуникаций.

Key words: nonlinear dynamics, Gunn instability, chaotic millimetre-wave oscillator, period multiplication, fractal oscillation, experimental observations.

Introduction

The past decade has seen heightened interest in the exploitation of chaos for useful applications in engineering systems. One application area that has attracted a great deal of attention is communications because of the potential benefits that can be gained from using chaotic signals for communications, including robustness in multipath environments, ease of spectrum spreading, added security, etc [1–2]. To achieve a success in developing of the chaos-based systems one should have reasonable chaotic oscillators [3]. Chaotic spatio-temporal oscillations occur in a variety of dissipative nonlinear dynamic systems in physics, chemistry and biology [4]. An example, which is of particular current interest, is the nonlinear dynamics of current oscillations in semiconductors in regime of the nonlinear charge transport [5]. A detailed discussion of the origin and the use of chaotic oscillations in GaAs semiconductors with Gunn effect is the subject of this paper.

Ridley and Watkins in 1961 and Hilsum in 1962 first presented the phenomenon of a negative differential mobility in compound multivalley semiconductor materials [6, 7]. Soon after their predictions, Gunn in 1963 made the experimental discovery of oscillating microwave current in bulk *GaAs* samples with ohmic contacts subjected to the high electric fields [8]. Kroemer in 1964, 1966 explained the oscillation observed by Gunn with a "two-valley" model based on the above mentioned works [9, 10]. At low applied fields the electrons occupy the central valley and exhibit the high-mobility relationship between the electron velocity and the applied field. However, as the field approaches a threshold value determined by the intervalley energy gap the electrons transfer into the low-mobility state. There is a consequent drop in electron velocity to the satellite valley's saturated drift velocity. This region of negative differential mobility gives rise to the device's bulk negative resistance and hence its ability to convert direct current power into microwave frequency power. Typical contemporary applications for Gunn diode oscillators include local oscillators in the range from 10 GHz to above 150 GHz, voltage controlled oscillators, radar and communication transmitters.

A conventional GaAs Gunn diode consists of three layers; one of a relatively low doped transit region ($\sim 10^{16}\ cm^{-3}$ and approximately $2 \mu m$ thick for operation at 94 *GHz*) sandwiched between two very highly doped contact layers, forming a n^{+}-n^{-}-n^{+} structure. The application of an external voltage V_{dc} (dc bias) exceeding a high-field threshold value ($E_{th} \sim 3.5\ kVcm^{-1}$ for *GaAs*) leads to periodic formation near one contact n^+ and propagation to another contact n^+ of bunches of electrons (high-field domains) and causes microwave transit oscillation in an external circuit. This oscillation usually referred to as Gunn oscillation has been extensively studied by various experimental, analytical and numerical techniques.

Having found a system with an own oscillation due to travelling-wave motion, it is natural to ask whether harmonic forcing would lead to chaos with spatial structure. A few research groups have carried out computer simulation using the drift-diffusion relations and showed that the nonlinear interaction between the internally generated domain mode and an external microwave signal may exhibit quite complicated behaviour. Among the obtained phenomena were mode locking and spatiotemporal chaos in driven Gunn-effect devices [11–13], fractal, non-chaotic behaviour in quasi-periodically driven microwave TEDs [14], subharmonic bifurcations of current oscillation period and evolutionary dynamics [15–17], multidomain regime and spatiotemporal chaos in Gunn diodes under impact ionization conditions [18, 19], and spatial solitons [20]. It was also shown that there are some qualitative similarities between the operation of the driven Gunn-instability devices and the operation of the relaxation oscillators with modulated threshold [21–23]. A drift-diffusion Gunn effect model was used to analyse phase resetting of transit Gunn oscillations perturbed by a single electric impulse. From the analysis of the response phase curves it was inferred the existence of a phase singularity [24, 25]. This phenomenon connected with the considerable suppression or maintenance of the travelling charge layers only at the certain phases and amplitudes of the impulse applied. It seems possible that the Gunn-effect model may be applicable in investigations of biological oscillators, many of which can be described by relaxation models and have the phase singularity [26].

In these works mainly the results of numerical simulation of periodically driven Gunn diodes were described. The complicated dynamics due to spatial-temporal instabilities and mode competition makes the theoretical modeling of such systems quite difficult. Thus, it is not clear whether the results are experimentally observable. Moreover, the used model systems are practically not experimentally accessible. To study real Gunn oscillation, it is convenient to use the well-known Gunn oscillators. Their operation gives a lot of nonlinear phenomena that can not be explained by traditional theoretical models. Among the experimental results special attention should be given to (i) the appearance of a multifrequency microwave oscillation with small frequency difference ($\Delta f \sim 10^6$-10^8 Hz) between its components, (ii) the complicated low frequency oscillation (10^1-10^8 Hz) in biasing circuit, and (iii) the operation in the W-band on the second or the third harmonic of the transit frequency [27–29]. The appearance of a self-excited oscillation when resonant frequency of a microwave circuit did not coincide with the transit frequency of the Gunn diode was not clear either. In this case the only passive filtration of the transit oscillation by the resonant circuit does not explain considerable initial amplitude of the self-excited oscillation. It was also experimentally observed that the Gunn effect semiconductor gives rise to anomalously large low-frequency current noise over a wide range of fields beyond the high-field threshold value. The spectral density was measured by connecting a standard pure resistor parallel to the sample and measuring the power consumed at the resistor. The low frequency noise was more than 10^3 times slower than the basic Gunn oscillation, which corresponds to the domain transit time [30, 31].

These effects, usually classified as undesired, are clearly observed when dc biasing voltage does not exceed (2-2.5)V_{th}, where V_{th}- is the threshold voltage of the Gunn diode current-voltage characteristic. Nowadays, when our knowledge of the self-oscillating systems nonlinear behaviour has been increased, one can predict that the most of those phenomena can be explained by the nonlinear dynamics of the Gunn current instabilities. The nonlinear dynamics of the Gunn diodes included in a microwave resonator was experimentally investigated by using of the 3-5 and 35-50 GHz Gunn oscillators [31–36]. A great variety of different modes of complicated nonlinear behaviour has been observed.

The results obtained can be used to design chaos free Gunn oscillators. But nowadays, more attractive stimulus to study self-oscillating structures including in a resonator - mainly connected with the highly nonlinear-dynamic phenomena that can arise due to nonlinear charge transport in the presence of an external resonant circuit.

This paper describes the numerically and experimentally observed Gunn oscillator nonlinear phenomena and may give way to an interest in better-focussed numerical modeling of such systems.

We tried to explain theoretically the obtained data and to provide predictions and suggestions for further studies.

Gunn chaotic oscillator design

Here the brief description of the Gunn chaotic oscillator is given. Figure 1 shows a typical realisation of a millimetre wave oscillator with passive means for stabilisation and tuning. It consists of an appropriate rectangular waveguide section tapered to about half the height, terminating in a variable backshort. The cut-off frequency of the output waveguide is about 28.8 *GHz* that is less of the transit frequency of the Gunn device used. In addition, the oscillator contains a coaxial bias line with filter section and thin post ending disc, and the variable backshort for tuning. The packaged GaAs Gunn diode having the epitaxial layer thickness of the order of $3\mu m$ has been investigated. It was centrally located under a radial disc. Each of the elements has an associated impedance, inductance and/or capacitance. The resonant-disc circuit is considered also as an efficient quarter-wave impedance matching transformer between the device and the waveguide.

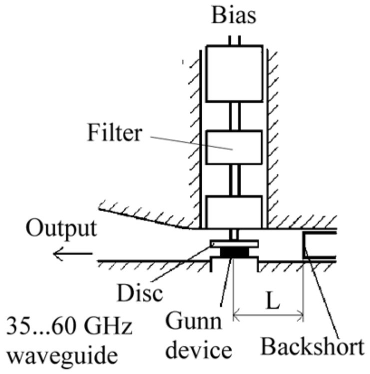

Figure 1. Gunn chaotic oscillator with coaxial bias line

Thus, the diode can be regarded as a negative resistance and a capacitance. The package gives the additional capacitance and inductance. The resistance of the package is designed to be negligible.

The complex coax/waveguide circuit exhibits many not always definable resonances at the frequencies corresponding to the Gunn transit frequency. However, the most important is a resonance of the entire coaxial line, including a filter, post, disc and device [27, 34]. The resonance usually provides a microwave resonant circuit at the fundamental operating frequency of the Gunn diode, usually 30-45 *GHz*. The bias post behaves as an inductor at the moment when the disc exhibits the properties of a capacitor. The resonant frequency f_{res} of the entire resonant circuit including the post-disc configuration and the waveguide cavity can be tuned over a wide frequency range by moving backshort and device position.

Thus, our experimental physical model is the Gunn device with the transit frequency f_0 depending on the bias voltage V_{dc}, which is placed into microwave waveguide resonant circuit with the frequency f_{res} of the main mode (figure 2).

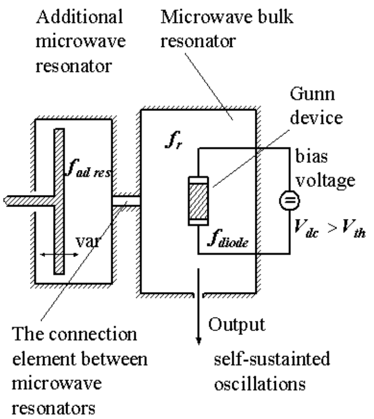

Figure 2. Experimental physical model

In this figure we can also see the additional bulk resonator which was not shown in figure 1. It is clear that the circuit dimensions have an important influence on the operation of a Gunn device.

Experimental observations

Experimental results show that the usual single-frequency regime of the Gunn oscillator operation is observed only if bias voltage V_{dc} exceeds some value V_{sw}> (2-2,5) V_{th} [16, 21]. The voltage V_{sw} is the voltage of a jumping transition of the output signal into regime of the single-frequency or, sometimes, two-frequency generation. Complicated oscillation $V_c(t)$ appears when $V_{th} < V_{dc} < V_{sw}$ [34, 35]. Our observations have made it possible to represent the signal $V_c(t)$ by the sum of two components, i.e.,

$$V_c(t)=V_{c1}(t)+V_{c2}(t). \qquad (1)$$

$V_{c1}(t)$ is in the radiofrequency range (0,01… 350 *MHz*) and has continuous or quasi-line spectrum with frequency components $F_p = p \cdot F_1$, where $p = 1, 2, \ldots N$. This signal has been obtained by us-

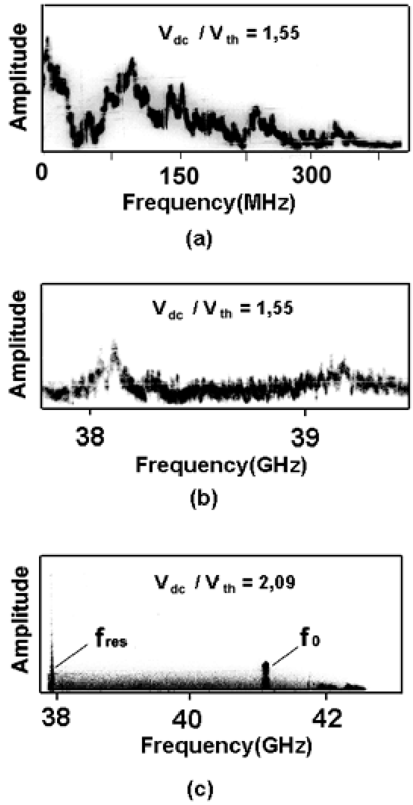

Figure 3. Spectra of the Gunn oscillator output signal: (a) - radiofrequency part $V_{c1}(t)$, (b) - microwave part $V_{c2}(t)$, (c) - spectrum after jumping transition into regime of the two-frequency generation

ing of a wide-band antenna located near the oscillator and connected to the input of an appropriate high-frequency spectrum analyser and an oscillograph. $V_{2c}(t)$ is in microwave range and has continuos noiselike spectrum.

The experimentally obtained spectra of $V_{c1}(t)$ and $V_{c2}(t)$ and the waveforms of $V_{c1}(t)$ are shown in figures 3 (a), 3 (b) and figure 4, respectively.

We suppose that such a complicated signal is a result of the nonlinear interaction between the transit Gunn oscillation with frequency f_o and the oscillation with frequency f_{res} arising in the resonant circuit due to the negative Gunn-effect conductivity. In other words we suppose that the forming of the radiofrequency component $V_{c1}(t)$ of the resultant signal is the condition of the coexistence of the interacting microwave oscillation with frequencies f_0 and f_{res}. And so the components $V_{c1}(t)$ and $V_{c2}(t)$ are closely connected with each other. It was noticed that they could exist only together. In our experiments we tried to establish the very nature of these signals′ interconnection.

The measurements have shown that the basic frequency F_1 is about 1-2 *MHz* for V_{dc} values near the threshold voltage of the Gunn diode and increases in steps of 8-15 times together with the growth of V_{dc}. The measured characteristic is shown in figure 5 by curve 1. The movement mainly proceeds by ″jumps″ of the frequency F_1. The shape of the microwave part of the spectrum does not change significantly with the growth of V_{dc}. It should be noted that the typical quasi-line spectrum of V_{c1} transforms into continuous one, like shown in figure 3 (a), when the value of V_{dc} is in the region of the sudden change of F_1. To explain this curve we should take into account that the data in figure 5 were obtained under the following conditions:

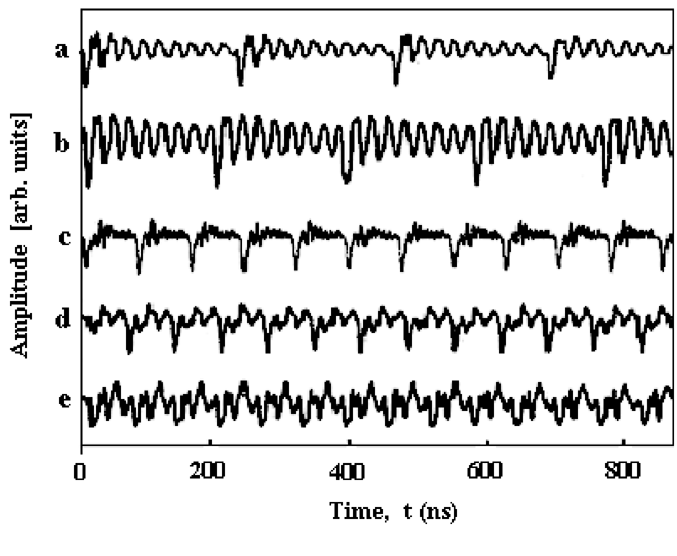

Figure 4. Time series of the RF part of the signal: *a* — V_{dc}/V_{th} = 1.14, *b* — 1.17, *c* — 1.58, *d* — 1.71, *e* — 1.96. The time scale start is arbitrary

f_{res}≈const, f_0=var.

Figure 5 shows also the calculated curve $f_0\ (V_{dc})$ inferred from a one-dimensional model of a *GaAs* Gunn diode of the length of $3\mu m$ [21]. One can see the obvious accordance in behaviour of the experimental approximate $F_1\ (V_{dc})$ curve 1 in this figure and the calculated $f_0\ (V_{dc})$ curve 2. It is seen, for example, that the rapid change of the transit frequency f_0 near the threshold value of V_{dc} is in accordance with the same rapid change in F_1 at the little values of V_{dc}/V_{th}.

To construct a model of the frequency F_1 jumping phenomenon in Gunn oscillators let us start considering the following expressions, known from the theory of periodically forced oscillators:

$$f_0=F_1\cdot n, \qquad (2)$$

$$f_{res}=F_1\cdot m, \qquad (3)$$

where n and m are integer. In our case we suppose that f_{res} is similar to a frequency of an applied forcing signal. If a rotation number $\rho = n/m$ is rational (where n and m are relatively prime) – then every solution with initial conditions near the torus will approach a periodic orbit on the torus which winds n times around the meridian in m forcing periods. If ρ is irrational, then every solution on the torus densely covers the torus (quasiperiodic dynamics).

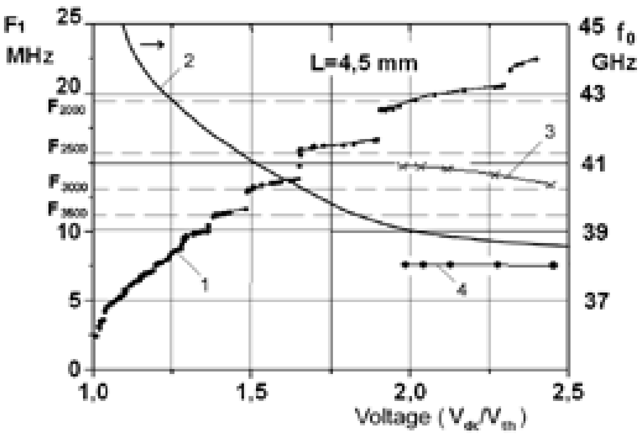

Figure 5. Basic frequency of the RF part of the output signal (curve 1) and the calculated $f_0\ (V_{dc})$ characteristic (curve 2) vs the applied dc voltage

Middle values of F_{1m} of the each frequency step in figure 5 can be determined by using of the expression (3). The expression should be modified as follows

$$F_{1m}=f_{res}/m, \qquad (4)$$

where $f_{res} \approx 40$ *GHz* is practically equal to the operation frequency of the Gunn oscillator when $V_{dc}>V_{sw}$ and the values of $m\cdot 10^{-3} = 2, 2.5, 3.0, 3.5\ldots$ were found empirically. In figure 5 some calculated values of F_{1m} are shown by dashed lines. They are in good agreement with the experimental curve. A little change of the frequency F_1 of the each step can be explained by the process of the oscillator pulling. Figure 3(c) shows how the spectrum in figure 3(b) has changed after a jumping transition of the oscillator into regime of the two-frequency generation at $V_{dc}>V_{sw}$. The signal $V_{c1}\ (t)$ disappears just at the time of the transition. According to our model we can assume that the less frequency component in figure 3(c), shown by curve 4 in Fig. 5 is the frequency f_{res} of the resonant external circuit and the greater one is the own Gunn frequency f_0 (curve 3). By changing V_{dc} one can easy prove it. In this case the frequency f_{res} has to remain practically invariable. The behaviour of experimental curves 3,4 is in good agreement with the model predictions.

As we see, the dynamical unstable balance described above leads to the noiselike microwave spectrum at the Gunn oscillator output. The main reason of such a spectrum seems to be connected both with natural frequency fluctuations of the interacting signals and some characteristics of the resonant circuit. The experiments indicate that an additional microwave resonator tuning can considerably regulate parameters of the output signal. For that the cavity resonator has been inserted into the microwave resonator of the Gunn oscillator (see figure 2). It has been found that the coherence degree of both $V_{c1}(t)$ and $V_{c2}(t)$ signals can simultaneously be improved by the certain tuning of this resonator. The chaotic spectrum of the microwave signal $V_{c2}(t)$ and the quasi-line spectrum of the radiofrequency signal $V_{c1}(t)$ transform into the quasi-line and line spectrums, respectively. The primary spectra were earlier displayed in figures 3(a) and 3(b). The spectra transformed are shown in figure 6. In the process of frequency tuning one can see that the basic frequency F_1 also changes. In figure 7 frequency F_1 is plotted as a function of the additional resonator frequency. The jumping transition of F_1 confirms our theoretical predictions.

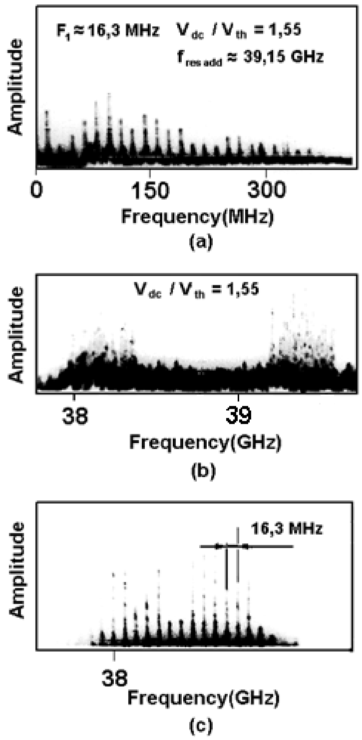

Figure 6. Spectra of the Gunn oscillator output signal after tuning of the additional microwave resonator: (a) - radiofrequency part, (b) - microwave part, (c) - enlarged part of the microwave spectrum in this figure

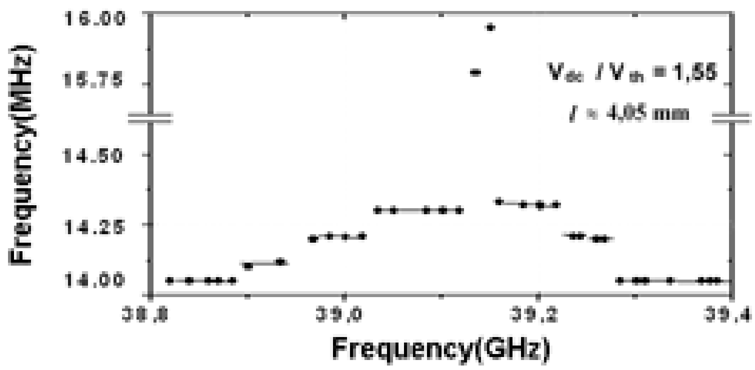

Figure 7. Variation of the basic frequency f_{c1} of the Gunn oscillator output signal in the process of tuning of the additional microwave resonator

Gunn oscillator shown in figure 1 has also been investigated without disc resonator. In this case the main resonant circuit is a piece of waveguide with the length of l. The experimental data obtained show that under certain values of V_{dc} and l the radiofrequency part of the output signal has a fractal character. Its complete spectrum consists of several components (up to 5) having the self-similar shape. The presence of a fractal attractor can be seen in figure 8 where the time components of one and the same signal are presented.

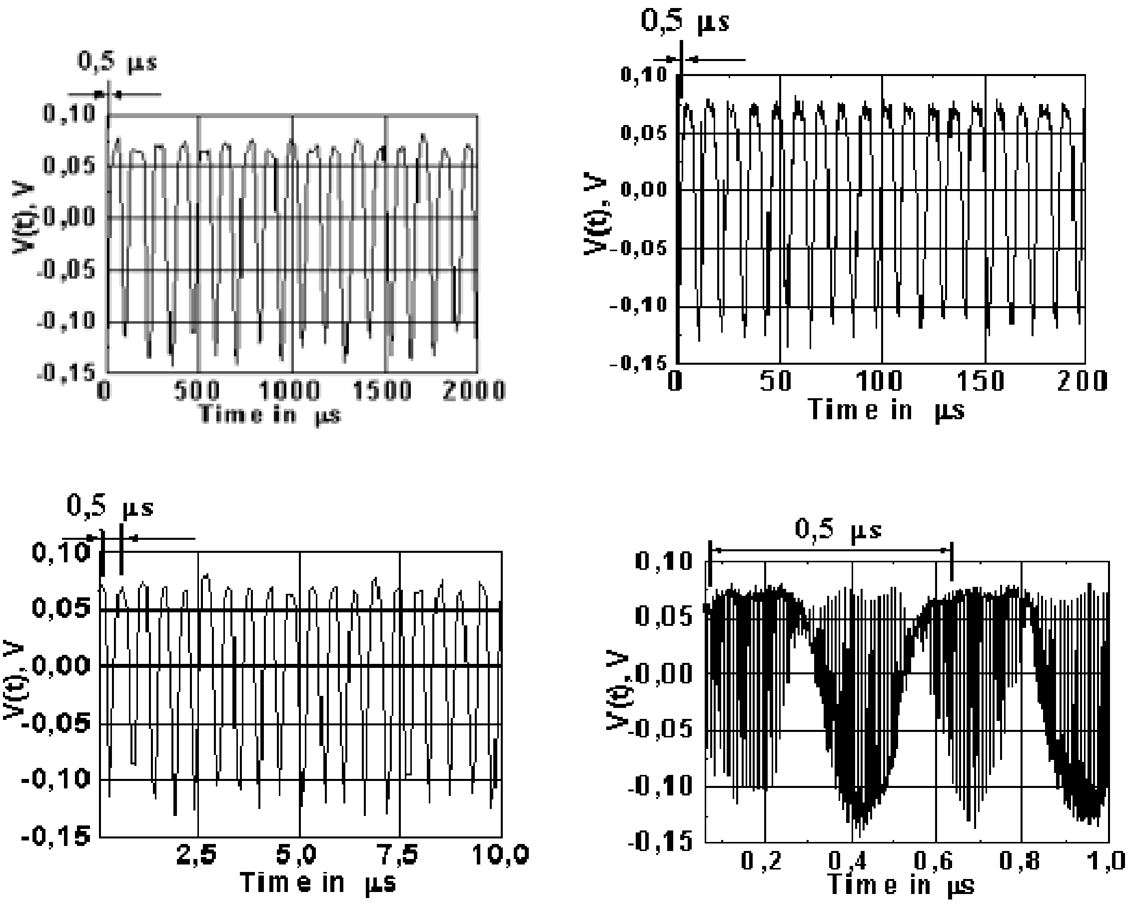

Figure 8. The shape of the complicated signal for the oscillograph different timebases

They were obtained for the different time bases of the digital oscilloscope. The ratios of their amplitudes have not been retained. More full version of the signal one can find in our previous study [36].

Discussion and conclusion

We have introduced the experimental results of the self-oscillating chaotic system consisting of a Gunn device placed into microwave waveguide resonant circuit. It was shown that the nonlinear dynamics plays a very important role in Gunn oscillators operation. The nonlinear interaction of the oscillations at $V_{dc}>V_{th}$ leads to the very complicated signal and determines the transition into usual single-frequency regime at $V_{dc}>V_{sw}$.

Based on a number of experiments carried out we have concluded that Gunn diode placed into microwave resonant circuit may exhibit large-scale noiselike, as well as coherent, behaviour. The main nonlinear properties of such an oscillatory system can be explained by the nonlinear interaction of the natural Gunn oscillation with the self-sustained oscillation arising in the microwave resonant circuit. The resultant complete signal is often similar to a polar-modulated one. The middle frequency of the microwave noiselike carrier is greater in $10^3 \ldots 10^5$ times than the basic frequency of this signal envelopes. The full spectrum of the signal consists of the quasi-line radiofrequency part, which is practically the envelopes spectrum and the noiselike microwave spectrum. They can exist only together because the forming of the radiofrequency subharmonic oscillation is the condition of the coexistence of the microwave oscillations interacted. The radiofrequency oscillation can be recorded in the biasing circuit of the oscillator by an oscilloscope or a spectrum analyser. It should be noted that the frequency fluctuations of this part of the signal are reduced in $10^3 \ldots 10^5$ times in comparison with the fluctuations of the microwave oscillation (see expression 3) and so they have more orderly spectrum (quasi-line instead of noiselike). It is surprising that the Gunn diode oscillatory system can organise its behaviour on such a large frequency scale. But whether the properties described above are common or they characterize only the system under consideration. To get the answer we have also investigated the nonlinear dynamics of another Gunn oscillator designed with coaxial resonant circuit and having the operation frequency in the range of 5-6 GHz. It was found that the main properties were kept the same. In particular, we have found that the shape of the characteristic showed in figure 5 is very similar to the same one of the coaxial oscillator and the output signal consists also of the radiofrequency and microwave parts.

The coherence degree of the oscillatory system can be improved by an additional microwave resonator tuning. Needless to say, our attempts to change the output microwave signal parameters by the external radiofrequency signal have appeared to be a failure. But it could easily be done by suitable microwave forcing signal.

The examples of the self-oscillating behaviour of this type have been reported from almost all branches of science, including human physiology [38]. For instance, wide range of biological cells show general oscillatory phenomena. Comparing the frequency- and intensity dependent response of the yeast cells with the behaviour of an externally disturbed nonlinear resonator, some similarities can be observed, provided the oscillating model system is self-sustained [39, 40]. Other examples one can observe in some musical instruments and in the production of vocal sounds. In reed instruments a reed is a nonlinear oscillator which vibrates and makes sound non-sinusoidal signal when the instrument is played. This signal excites some distributed-constant line (it can be a tube). The oscillation arisen in the line acts in its turn on the reed vibrations that, finally, affords to synchronise the main frequency of the reed oscillation with resonant frequencies of the distributed-constant line. In general terms, the human vocal tract is also considered as a resonant tube, with one side branch for the mouth and another for the nose [41]. The periodic vibrations normally associated with vowels result from the nonlinear interaction of the periodic pulses created by the glottis and air stream from the lungs with the oscillations excited in the vocal tract. And so it is not surprising that the waveforms of the radiofrequency part of the Gunn oscillator signal showed in figure 4 are very similar to the waveforms of the vowel sounds [42]. This phenomenon can be explained by the similar nature of the systems under consideration.

Such a large-scale behaviour of the output Gunn signal is closely observed in living systems. For example, the rather like properties were found by researching human circadian rhythms which imply a high degree of coherence. Unexpectedly, the involved person's deep body temperature and sleep-wake cycles had a remarkable sensitivity to weak 10 Hz fields which were able to entrain free-running body rhythms and even force a 23-hour daily cycle [43]. The ratio of these periods is $\sim 10^6$ that is in reasonable agreement with our experimental findings. A better understanding of these phenomena may be also significant for treatment of some dynamical diseases [44]. It should be noted that such kind of the chaotic oscillators are also very necessary for complementary medicine and biology, which investigate the effects of the millimeter-wave radiation on people [45].

We believe that the nonlinear Gunn dynamics described above may stimulate further development of models of far more complex self-oscillating chaotic systems based on the Gunn effect and they appear useful for modeling the common genetic properties of the above-mentioned and other similar systems. Further experimental and numerical investigations based on the Gunn effect can result in appearance of unique chaotic generators for the chaos-based digital communication systems [1, 2].

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Abstract

Nonlinear dynamics in Gunn devices that can exhibit chaotic behaviour is discussed. Evidence for such behaviour is given by laboratory experiments, by computer simulations, and, where available, by simple mathematical reasoning.

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