THE PHASE STABILITY OF NANOSECOND GUNN OSCILLATORS

Vasily Y. Kozhevnikov[a], *Andrey* V. Kozyrev[b],
Vladimir Y. Konev[c], *Aleksey* I. Klimov[d]

[a] Institute of High Current Electronics, Laboratory of Theoretical Physics, Tomsk, Russian Federation,
e-mail: Vasily.Y.Kozhevnikov@ieee.org, **corresponding author**,
ORCID iD: https://orcid.org/0000-0001-7499-0578

[b] Institute of High Current Electronics, Laboratory of Theoretical Physics, Tomsk, Russian Federation,
e-mail: kozyrev@to.hcei.tsc.ru,
ORCID iD: https://orcid.org/0000-0002-7078-7991

[c] Institute of High Current Electronics, Laboratory of Nonlinear Electrodynamic Systems, Tomsk, Russian Federation,
e-mail: konev@lnes.hcei.tsc.ru,
ORCID iD: https://orcid.org/0000-0001-8728-6491

[d] Institute of High Current Electronics, Physical Electronics Department, Tomsk, Russian Federation,
e-mail: klimov@lfe.hcei.tsc.ru,
ORCID iD: https://orcid.org/0000-0003-0953-1644

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Summary:

Introduction/purpose: Detailed theoretical and experimental studies have been carried out in order to investigate the problem of a phase stability in electrodynamically uncoupled Gunn oscillators.

Methods: The influence of modulating pulse instabilities has been investigated by means of computer simulation in the framework of a nonlinear one-dimensional theoretical model of the GaAs Gunn diode semiconductor active region. Experimental observations were also conducted including microwave measurements and antenna far-field estimation. They confirm the main theoretical results and extend the key work conclusions.

Results: It was shown that the initial phase of the microwave oscillation out of the Gunn oscillator is independent of internal noises of the semiconductor structure and can be fixed only by the modulating voltage pulse.

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Conclusion: Gunn-diodes based microwave oscillators were stabilized using the leading edge of the voltage pulse from the modulating power supply. These results open up serious prospects for designing antenna phased arrays based on Gunn oscillators without mutual feedback (electrodynamically independent).

Key words: microwave circuits, space-charge-limited devices, Gunn effect devices.

Introduction

The problem of phase synchronization in microwave oscillators has been of interest for decades (Schamiloglu, 2012). Creation of coherent high-frequency radiation sources offers great opportunities for the development of modern microwave technology. It allows to carry out the coherent spatial summation of radiated power and to provide the coherent signal accumulation mode in the near- and far-field radar systems. In turn, this can significantly increase the capabilities of receiving and transmitting devices (e.g. noise-to-signal ratio). The use of coherent microwave pulse oscillators will significantly improve the location range resolution. Furthermore, these capabilities allow developing active phased arrays modules.

The analysis of the excitation of microwave oscillations conventionally assumes the decisive role of noise in phase setting, resulting in randomness of the phase (Holliday, 1970). The phase stabilization of microwave oscillators is generally attained by using injection locking and phase locking providing strong electrodynamic feedback between oscillators (Pikovsky et al, 2010). The possibility of obtaining coherent oscillations from electrodynamically independent Gunn oscillators remained undiscovered for a long time. However, one more way has been discovered - to use a modulating voltage pulse (Vvedensky et al, 1975; Vvedensky et al, 1985). Vvedensky with co-authors explain the observed phase stabilization effect by a current spike which arises in the resonator of a Gunn oscillator and sets the initial phase (“shock” excitation). It has been emphasized that a reliable phase stabilization requires a rather short modulating pulse rise time (of about the oscillation period).

Based on the hypothetical possibility of synchronizing an oscillator without feedback, in our later experimental papers dealing with two electrodynamically independent nanosecond X-band Gunn oscillators producing ~ 30 W of microwave power (Gubanov et al, 2010; Konev et al, 2011), we observed phase stabilization and synchronization when the oscillators were excited from a common modulator with the modulating pulse rise time much longer than the oscillation period. The minimum standard deviation of the phase difference between the oscillator signals was ~ 2 ps at a modulating pulse rise time of 6.5 ns (Konev et al, 2013).

These observations have been explained by means of a computer simulation and additional experiments. The results obtained suggest that the phase stabilization of a Gunn oscillator by a modulating voltage pulse, $U_{GD}(t)$, is governed by the intrinsic properties of the Gunn diode semiconductor. Specifically, the microwave oscillation phase is stabilized, once the semiconductor starts operating in a mode of negative differential resistance and a first high-field domain appears. This corresponds to a threshold voltage $U_{GD} = U_{th}$ reached at some point of the modulating pulse leading edge. The discovered effect was rather unexpected for us because we failed to find similar interpretation in the previous investigations.

This paper presents an extended review of the theoretical and experimental results regarding the phase stabilization of an uncoupled (independent) Gunn-diode based oscillator. The results convincingly suggest the possibility of the initial phase fixation in electrodynamically uncoupled X-band Gunn oscillators. This phase fixation is carried out only by a modulating voltage pulse applied to the oscillator.

Theoretical results

The initial experimental work led us to the idea that widely used electrotechnical computational methods (for example, the technique of replacing a semiconductor Gunn diode with an equivalent RCL circuit) are not sufficiently informative for studying the phase stability of a device. So we proposed theoretical studying of electronic processes in Gunn diodes to be based on a numerical simulation of the active layer of the Gunn diode semiconductor crystal in a non-stationary model. All proposed simulations have been carried out using the nonlinear local field model (McCumber & Chynoweth, 1966; Kroemer, 1966). The semiconductor structure of the Gunn diode is considered to be a GaAs one-dimensional crystal with two ohmic contacts at the opposite faces. Its microscopic structure in calculations is given by simplified quasihomogeneous doping profile containing localized inhomogeneity, the so-called "notch" (Figure 1).

In most computations, the quasihomogeneous semiconductor was assumed to have a donor concentration of 10^{15} cm^{-3}. The semiconductor layer diameter and length were 300 μm and 12.5 μm, respectively. A high field domain was formed due to the existence of a 0.6 μm long region of lower donor concentration ($0.9 \cdot 10^{15}$ cm^{-3}) located 0.6 μm away from the cathode ("notch" region). To describe the relation between the electron velocity and the electric field strength, a well-known approximation

(McCumber & Chynoweth, 1966) was used with the electron mobility taken equal to 8000 $cm^2/(V·s)$ and the saturation drift velocity of carriers at high field (4000 V/cm) equal to 10^7 cm/s. The diffusion coefficient was taken constant and equal to 200 cm^2/s.

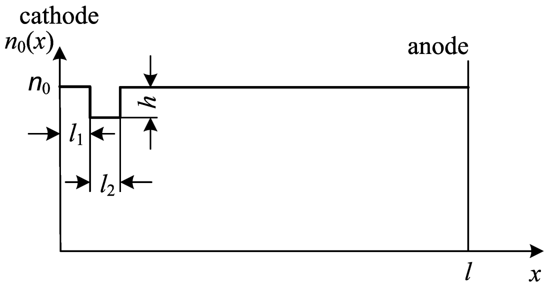

Figure 1 – Simplified active layer quasihomogeneous doping profile $n_0(x)$ of the Gunn diode semiconductor
Рисунок 1 – Упрощенный профиль квазиоднородного легирования активного слоя $n_0(x)$ полупроводника с диодом Ганна
Слика 1 – Поједностављени профил квазихомогене легуре активног слоја $n_0(x)$ полупроводника са Гановом диодом

Two important cases of connecting Gunn diodes were considered. In the first case, a simulation was performed for the simplest Gunn oscillator circuit consisting of a Gunn diode, a modulator, and a current-limiting resistor (R = 1 Ω) connected in series (Kozhevnikov et al, 2013).

In the other case, the Gunn oscillator equivalent circuit (with parameters R_1 = 1 Ω, L_1 = 0.5 nH, C_1 = 0.5 pF, L_2 = 1.2 nH, C_2 = 1.2 pF, R_2 = 0.5 Ω, L_3 = 0.5 nH) contained a resonator (Figure 2) to take into account the effect of the electric field on the processes occurring in the semiconductor layer (Konev et al, 2013). The units of this circuit and its parameters were specified to match the design of the oscillator used in our experiments (Gubanov et al, 2011) and so that sinusoidal microwave oscillations with a carrier frequency of 10 GHz were excited at the load R_2 simulating the output waveguide. The voltage pulse generated by the modulator had a trapezoidal shape and its instability was simulated by variations in the rise time t_e and the amplitude U_0. These variations produced phase deviations in the microwave pulse. For instance, for the circuit with resistive load, the variation Δt_e = ± 0.05 ns about an average value of 1 ns gave a current phase deviation Δt_{ph} equal to ± 0.016 ns (Figure 3*a*). For the circuit with a resonator under the same conditions, the Δt_{ph} was ± 0.022 ns (Figure 3*b*).

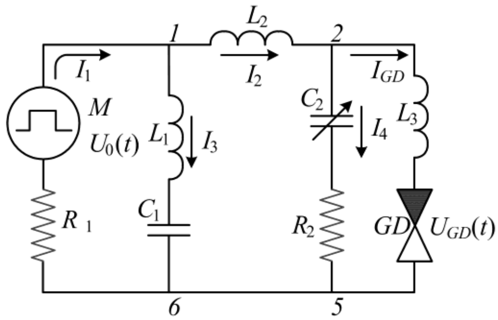

Figure 2 – Equivalent circuit simulating a Gunn oscillator in a resonator
Рисунок 2 – Эквивалентная схема, моделирующая генератор Ганна в резонаторе
Слика 2 – Еквивалентно коло које симулира Ганов осцилатор у резонатору

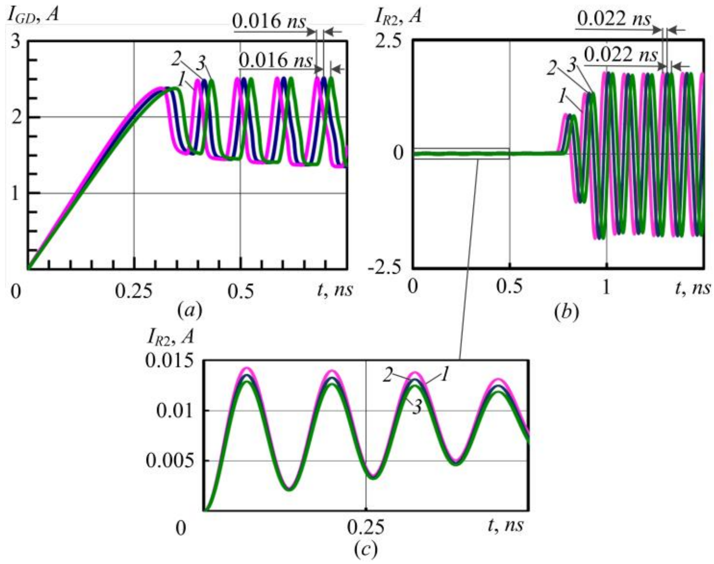

Figure 3 – Time dependences of the Gunn diode current at voltage pulse rise times t_e of 0.95 (1), 1 (2), and 1.05 ns (3) for the single-layer structure (a) in the circuit with resistive load and (b) at the load R_2 in the equivalent circuit, U_0 = 20 V.
Рисунок 3 – Профили тока диода Ганна в контуре с резистивной нагрузкой (a) и на нагрузке R_2 в эквивалентной схеме резонатора на рисунке 3 (b):
t_e = 0.95 (*1*), 1 (*2*), and 1.05 ns (*3*); U_0 = 20 V.
Слика 3 – Напонски профили Ганове диоде у колу резистивног оптерећења (a) и на оптерећењу R_2 у еквивалентном колу резонатора на слици 3 (б):
t_e = 0.95 (*1*), 1 (*2*), and 1.05 ns (*3*); U_0 = 20 V.

The simulation has also shown that Δt_{ph} did not increase on increasing

t_e at a fixed U_0 and $\Delta t_e \neq 0$, whereas an increase in t_e at a fixed $\Delta t_e = 0$ and $\Delta U_0 \neq 0$ gave an increase in Δt_{ph}. This means that the modulating pulse amplitude noise is the main reason of the oscillator phase instability increase caused by the pulse leading edge rise.

For the circuit with a resonator, the effect of phase stabilization was observed in the background of “shock” excitation in the oscillatory circuit, as demonstrated in Figure 3*c.* As it was shown (Konev et al, 2013), the only microwave oscillations appeared due to “shock” excitation observed both in the simulation and in the experiment could be considered as some appreciable “noise”. The calculations show that in all studied cases, the oscillation amplitude of the Gunn diode current is about 1 A even in the first period when U_{GD} exceeds U_{th}, and this amplitude is noticeably higher than the above mentioned “noise” amplitude (Figure 3*b*). As a result, the observed phase deviation is defined by the instability of the modulating pulse rise time and amplitude, and the Gunn diode itself provides a stable phase during the excitation of the oscillatory process.

Experimental results

The experimental work was aimed to investigate the possibility of creating synchronized Gunn diodes oscillators. It includes several series of experiments. Most of experimental setups were carried out on nanosecond Gunn oscillators with one and two series-connected 3A762-type Gunn diodes. The use of two diodes implied, along with phase measurements, a study of the possibility for power enhancement. The oscillators were tuned to a carrier frequency of 10 GHz.

The first group of experiments have been conducted in order to measure the phase delay standard deviation with respect to the modulator pulse rise time (in Figure 4). The measurements were performed with a LeCroy WaveMaster 830Zi oscilloscope. The “delay” function was used to measure the standard deviations σ_{t1} and σ_{t2} of phase delay with respect to a certain time point during the modulating pulse rise $U_{DG}(t)$ for one and two series-connected Gunn diodes, respectively. The measuring channel for the modulating pulse had a working bandwidth of 1 GHz and each of those for the microwave signal had a working bandwidth of 13 GHz. The oscilloscope trigger voltage was ~ 500 mV.

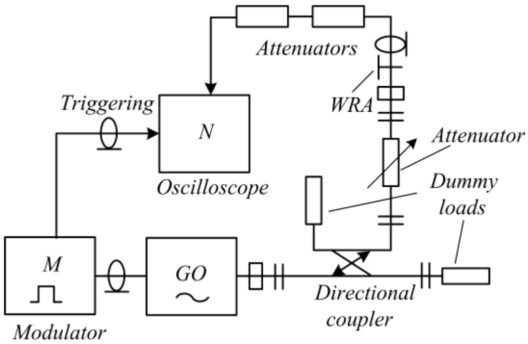

Figure 4 – Measuring circuit for the standard deviation of phase delay
Рисунок 4 – Схема измерения стандартного отклонения фазовой задержки
Слика 4 – Мерно коло за стандардну девијацију фазног кашњења

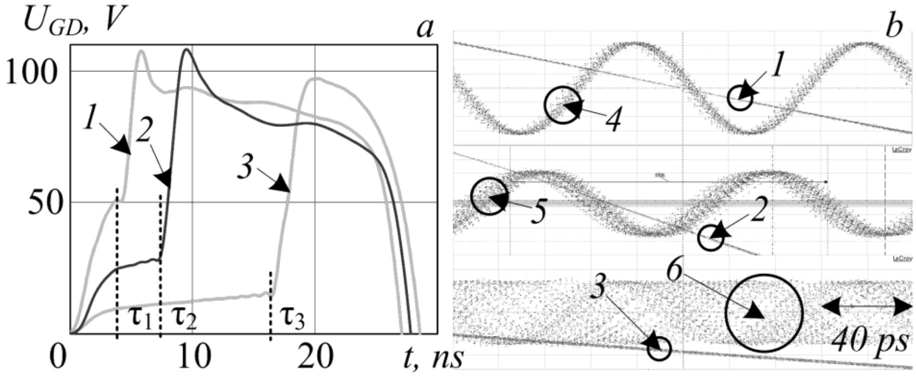

Figure 5 – (a) Oscillograms of the modulating pulse and (b) set of 2500 superimposed oscillograms of the modulating pulse and the microwave signal at different voltage rise times.
Рисунок 5 – (a) Осциллограммы модулирующего импульса и (b) набор из 2500 наложенных осциллограмм модулирующего импульса и СВЧ-сигнала при различном времени нарастания напряжения
Слика 5 – (a) Осцилограми модулационог импулса и (b) сет од 2500 суперпонираних осцилограма модулационог импулса и микроталасног сигнала у различитим временским интервалима пораста напона

The minimum standard deviations were σ_{t1} = 2.1 ps and σ_{t2} = 0.8 ps after excluding the oscilloscope jitter. The peak power with one and two diodes was ~ 30 and ~ 60 W, respectively. The much lower value of σ_{t2} compared with σ_{t1} suggests that the semiconductor structure has a stabilizing effect on the microwave oscillation phase.

In the experiments, we studied the influence of the voltage pulse rise time (rate of voltage rise dU_{GD}/dt) on σ_{t1}. For this purpose, chip inductors

L of 8.2 and 82 nH were connected in series with a Gunn diode between the modulator and the oscillator resonance chamber. Figure 5a and Figure 5b show the waveforms of the voltage pulse (1–3) and the microwave signal (4–6) for L = 0 nH (traces 1, 4), L = 8.2 nH (traces 2, 5), and L = 82 nH (traces 3, 6).

In the first case, the minimum standard deviation σ_{t1} was 2.1 ps; in the second case, it was 14.5 ps; and in the third case, the phase becomes unstable. The voltage rise times shown in Figure 5a are as follows: τ_1 = 4 ns, τ_2 = 7.2 ns, τ_3 = 16.4 ns. This dependence of σ_{t1} on the voltage rise time is explained by the fact that the phase deviation Δt_{ph} increases with increasing t_e due to some instability of the voltage pulse amplitude, as found in the simulation.

In the second experiment (Figure 6), we studied the phase synchronization of two oscillators with a peak power of 30 W which were connected in parallel and excited concurrently by a common modulator via strip lines of a geometric length of 120 cm (insulator – fiber glass laminate). This excluded the oscillators coupling via the modulator. Measurements were performed by a special procedure (Konev et al, 2011).

The modulating pulse rise time was 6.4 ns. Figure 7 shows the synchronized oscillograms of microwave signals 1 and 2 for these two oscillators. The oscillograms demonstrate that the microwave oscillation arising on time interval 4 due to the transition of the Gunn diode semiconductor structures to the mode of negative differential resistance is independent of the oscillations appeared within time interval 3 due to the “shock” excitation of the oscillatory circuit. It is seen that signal 2 (green) displays some phase failure.

Nevertheless, after several periods, signal phases 1 and 2 are aligned. On alternately switching off one of the Gunn oscillators, the oscillograms remained unchanged. Thus, a crosstalk-induced synchronization was excluded. The oscillations remained cophased during the whole microwave pulse with a full width at a half maximum of 16 ns.

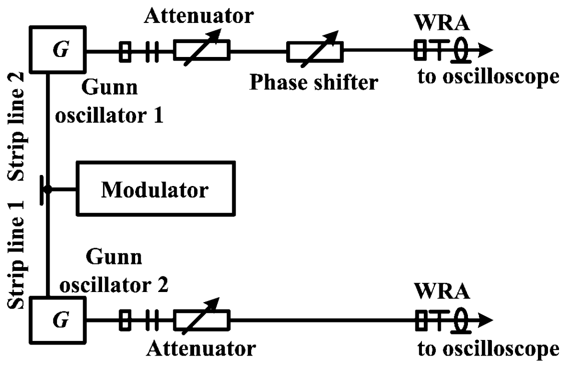

Figure 6 – Experimental measuring circuit for the syncronization of two independent Gunn oscillators
Рисунок 6 – Экспериментальная измерительная схема синхронизации двух независимых генераторов Ганна
Слика 6 – Експериментално мерно коло за синхронизацију два независна Ганова осцилатора

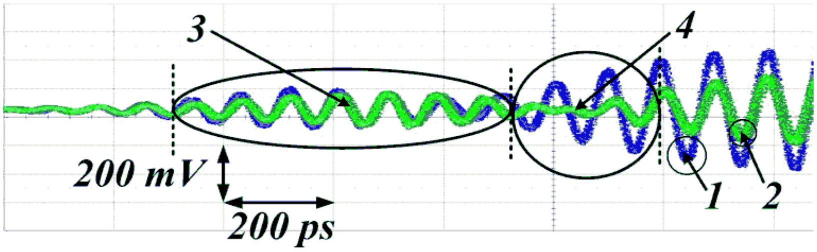

Figure 7 – Set of 2500 superimposed oscillograms of two Gunn oscillators
Рисунок 7 – Набор из 2500 наложенных осциллограмм двух осцилляторов Ганна
Слика 7 – Сет од 2500 суперпонираних осцилограма два Ганова осцилатора

As the measured deviation value was 2.1 ps, so it fits the phase stability criterion for the development of antenna active phased arrays. It was also established that the serial connection of two identical Gunn diodes led to a significant reduction of the standard deviation value as compared to the same value for a single diode. Both of these favorable factors prompted another experimental study of the antenna system wave field (Kozhevnikov et al, 2015). Its visual scheme is shown in Figure 8. The antenna system consists of two synchronized nanosecond X-band Gunn oscillators GO_1 and GO_2 connected to rectangular horns 8 via attenuators 2 and a phase shifter 3. The Gunn oscillators were fed from a single voltage source 1 through strip lines. The horn antennas 8 were arranged in parallel to each other at a distance a = 14 cm between them.

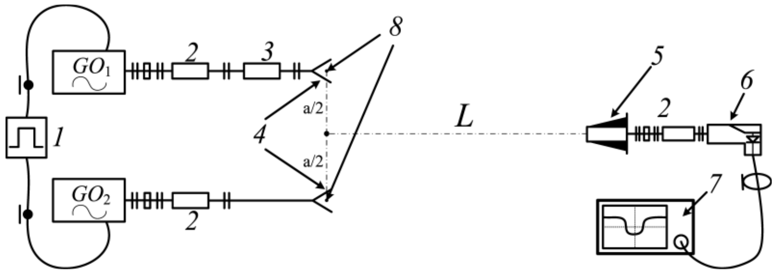

Figure 8 – Experimental setup of a wave field measurement of an antenna system
Рисунок 8 – Экспериментальная установка измерения волнового поля антенной системы
Слика 8 – Експериментална инсталација мерења таласног поља антенског система

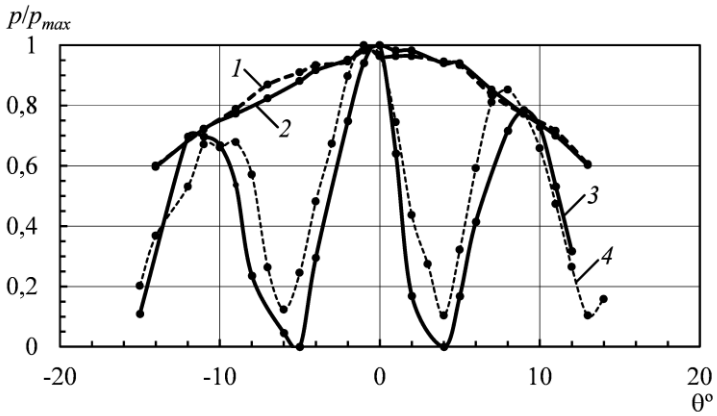

Figure 9 – Far-field measurement results: 1, 2 *– radiation pattern of each horn excited by an independent Gunn oscillator;* 3 *– microwave oscillations superposition of two horn antennas powered by a single standard oscillator with 500 us pulse duration;* 4 *– microwave oscillations superposition of two synchronized nanosecond Gunn oscillators*
Рисунок 9 – Результаты измерений в дальней зоне: 1, 2 – диаграммы направленности каждого рупора, возбуждаемые независимым генератором Ганна; 3 – суперпозиция СВЧ колебаний двух рупорных антенн с питанием от одного эталонного генератора с длительностью импульса 500 мкс; 4 – суперпозиция СВЧ колебаний двух синхронизированных наносекундных генераторов Ганна
Слика 9 – Резултати мерења у далеком пољу: 1, 2 – дијаграм зрачења сваког рога антене, побуђене независним Гановим осцилатором; 3 – суперпозиција микроталасних осцилација две рог антене са напајањем од једног стандардног осцилатора са трајањем импулса од 500 μс ; 4 – суперпозиција микроталасних осцилација двају синхронизованих наносекундних Ганових осцилатора

The receiving antenna 5 was connected to the waveguide semiconductor detector 6 through an adjustable attenuator 2. The detected signal was recorded with the Tektronix-5401 real-time oscilloscope 7 with 1 GHz operating band. The coherent summation of the wave field patterns from two horn antennas powered by a single standard oscillator with a 500 us pulse duration, and powered by two synchronized nanosecond Gunn oscillators is shown in Figure 9.

Conclusions

The studies show that the microwave oscillation phase in the Gunn oscillators is stabilized in an instant when the Gunn diode semiconductor structure passes to the mode of negative differential resistance. In the experiments, we did not find the influence of noises that can perceptibly affect the phase. Appreciable oscillations were only those arising due to the pulse excitation of the oscillator resonance system. Once the threshold voltage is reached and the first high field domain is formed, the current amplitude through the Gunn diode structure increases in a time of about the oscillation period, reaching a near-stationary value which is much higher than the noise and “shock” excitation values. Thus, the oscillation phase of the Gunn oscillators with a microwave power of several tens of watt (e.g., those based on 3A762 diodes), can be stable even at much longer modulating pulse rise time compared to the microwave oscillation period.

The discovered effect and the phase instability measurements results suggest prerequisites for the development of phased arrays. It requires a simple phase synchronization mechanism with only the voltage pulse of common modulator or several synchronized modulators that produce a repeatable modulating pulse without strict limitations on its rise time.

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ФАЗОВАЯ УСТОЙЧИВОСТЬ НАНОСЕКУНДНЫХ ГЕНЕРАТОРОВ ГАННА

Василий Ю. Кожевников[а], **корреспондент**, *Андрей В.* Козырев[а], *Владимир Ю.* Конев[б], *Алексей И.* Климов[в]

Институт сильноточной электроники, г. Томск, Российская Федерация

[а] Лаборатория теоретической физики

[б] Лаборатория нелинейных электродинамических систем

[в] Отдел физической электроники

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ВИД СТАТЬИ: обзорная статья

Резюме:

Введение/цель: Подробные теоретические и экспериментальные исследования были проведены для изучения проблемы фазовой устойчивости в электродинамически развязанных генераторах Ганна.

Методы: С помощью компьютерного моделирования в рамках нелинейной одномерной теоретической модели активной области полупроводникового GaAs-диода Ганна исследовано влияние нестабильностей модулирующего импульса. Также были проведены экспериментальные наблюдения, включая микроволновые измерения и оценку дальнего поля антенны, которые подтвердили ключевые теоретические результаты и расширили основные выводы работы.

Результаты: Показано, что начальная фаза СВЧ колебаний вне генератора Ганна не зависит от внутренних шумов полупроводниковой структуры и может фиксироваться только импульсом модулирующего напряжения.

Выводы: Генераторы СВЧ на диодах Ганна стабилизировались по переднему фронту импульса напряжения от модулирующего источника питания. Эти результаты открывают серьезные перспективы для создания антенных фазированных решеток на основе генераторов Ганна без взаимной обратной связи (электродинамически независимых).

Ключевые слова: СВЧ-схемы, устройства с ограничением объемного заряда, устройства на эффекте Ганна.

ФАЗНА СТАБИЛНОСТ НАНОСЕКУНДНИХ ГАНОВИХ ОСЦИЛАТОРА

Василиј J. Кожевников[а], **аутор за преписку**, *Андреј* В. Козирев[а], *Владимир* J. Конев[б], *Алексеј И.* Климов[в]

Институт за високострујну електронику, Томск, Руска Федерација

[а] Лабораторија за теоријску физику

[б] Лабораторија за нелинеарне електродинамичке системе

[в] Одсек за физичку електронику

ОБЛАСТ: микроталасна електроника
ВРСТА ЧЛАНКА: прегледни рад

Сажетак:

Увод/циљ: Спроведена су детаљна теоријска и експериментална истраживања ради испитивања проблема фазне стабилности у електродинамички раздвојеним Гановим осцилаторима.

Методе: Коришћењем рачунарске симулације у оквиру нелинеарног једнодимензионалног теоријског модела активне зоне GaAs полупроводничке Ганове диоде проучен је утицај нестабилности модулационог сигнала. Такође, извршена су експериментална испитивања, укључујући микроталасна мерења и процену далеког поља антене, која су потврдила кључне теоријске резултате и проширила основне закључке рада.

Резултати: Доказано је да почетна фаза микроталасних осцилација ван Гановог генератора не зависи од унутрашњег шума полупроводничке структуре и да се може детектовати само модулационим сигналом напона.

Закључци: Микроталасни генератори са Гановим диодама стабилизовани су на предњој ивици напонског импулса из модулационог напајања. Ови резултати потврђују да постоје озбиљни изгледи за стварање антенских фазних решетака на бази Ганових генератора без међусобне повратне спреге (електродинамички независне).

Кључне речи: микроталасна кола, уређаји са ограниченим пуњењем, уређаји са Гановим ефектом.

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