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TIME-DOMAIN SIMULATION OF SHORT-PULSE OSCILLATIONS IN A GUNN DIODE SYSTEM WITH TIME-DELAY MICROSTRIP COUPLING

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Time-domain simulations of active systems with Gunn diodes connected by sections of microstrip transmission lines (TL) are carried out. Self-generation of Gunn diodes mounted in various ways in the TL circuits has been investigated. Complex dynamics of electromagnetic field radiated into an open end of the TL are observed. Trains of high-frequency pulses are shown to emerge when active devices are separated from compact resonant circuits by extended sections of the TL providing a time-delayed feedback.

Keywords: high-frequency pulses, Gunn diode, delay line, time delay system.

1. INTRODUCTION

We perform time-domain computer simulations of nonlinear self-oscillations in distributed microstrip transmission line systems with active devices specified by negative differential resistance (NDR) of current-voltage characteristics such as of Gunn diodes and similar structures. There are two main goals of this research which concern both the theoretical and practical aspects of the problem:

1) Developing mathematical models, numerical techniques and computer codes for the efficient self-consistent time-domain simulation of high-frequency excitation in distributed systems with a strong time-delayed coupling between active devices connected by sections of transmission lines;

2) Investigating available options of microstrip implementation of nonlinear power combining (superlinear in the number of devices) and non-conventional spectral effects (ultra-wideband chaotic oscillations etc) for possible practical applications in high-frequency electronic systems (ultra-short pulse generation, noise radars, etc).

Microwave power combining has been investigated for a long time. Initially, there were lumped circuits being considered. Later on, waveguide network [1, 2] and quasi-optical array systems [3, 4] have been proposed. Despite numerous achievements [4, 5], efficient power combining remains a challenging problem. There are important physical reasons for this, such as the distributed character of systems whose size is large compared to the wavelength (especially, when considering open radiating systems), broadband and multi-frequency dynamics of oscillations, etc.

Nowadays, the major goal is the power combining in the THz bands where the power output of individual devices is intrinsically limited by the physical processes involved (the main relaxation channels in both the devices and the environment occur precisely in this domain). In the meantime, conventional design and simulation techniques (e.g., the impedance analysis method) are insufficient for these systems [6, 7], being only valid in a small-signal approximation for narrow-band applications. On the other hand, exact numerical methods (such as finite-difference time-domain ones [8]) require huge computational resources and are inappropriate in many cases.

The active character of devices characterized by instability and nonlinearity makes common simulation tools (e.g., Flomerics Micro-Strips, etc) inadequate for the rigorous modeling of such systems. Other software, such as SPICE, cannot cope with distributed systems where the wave propagation between the devices is an essential part of system operation. A promising approach is the use of hybrid numerical methods [9] that combine both the frequency-domain and the time-domain computations, though they also suffer from various limitations (narrow-band approximation etc).

For these reasons, the design of active structures is usually split in two separate stages dealing with either linear or nonlinear parts of the system. In this method, the attention is focused on passive components whose design is carried out in much detail. As a price for this simplification, some assumptions are supposed to be met such as the operation of the system in the narrow band or in a given set of a few narrow bands, etc.

In this work, we choose an alternative approach and focus our attention on the nonlinear part of the problem, while the linear part is chosen to be relatively simple. In this approach, the aim is the accurate self-consistent modeling of nonlinear effects through rigorous solutions of governing equations and, specifically, accurate time-domain simulations of nonlinear oscillations and non-conventional dynamics (chaos, pulses) emerging in various conditions [10-13]. As a practical issue, nonlinear power combining is investigated in a rigorous manner.

By reducing the linear part of the problem to the simplest form, we arrive at a set of discrete devices connected by sections of one-dimensional transmission lines, e.g., microstrips. Microstrips excited by solid-state devices are rather practical solutions for various applications. A study of one-dimensional models provides also a benchmark for testing various computational methods ranging from analytic approximations to advanced numerical tools.

In quasi-optical applications, parallel coupling of active devices in a single array is used for increasing the power output [4] (in microwaves, similar ideas were implemented in the waveguides by K. Kurokawa [1]). A one-dimensional analogue of this system is the parallel connection of transmission line circuits, with microwave power being radiated into an open infinite section of the line (the latter models the radiation of the electromagnetic waves from the antennas into free space in three-dimensional open systems).

As an alternative system, a series connection of active devices in a sufficiently long transmission line (a ladder-type oscillator) represents a simplified model of an open active structure with distributed elements that could be used for the spectrum modification of THz radiation. Our simulations of a chain of Gunn diodes [10] revealed complicated dynamics of the electromagnetic field in this system, though more detailed analysis of this structure is needed.

The interest in the systems of this kind is justified by their potential applications as the sources of chaotic signals for the emerging field of the noise radar technology [14]. This technology provides a number of benefits such as an ultra-wideband spectrum of radiation, simultaneous detection of the position and the velocity of the target, operation below the noise level of the environment, and other advantages. For these reasons, THz applications and, especially, MMIC implementations of these systems are of particular interest.

2. SIMULATION OF PARALLEL TIME-DELAY NETWORK OF ACTIVE DEVICES

Simulation approach outlined above was applied earlier to a few kinds of time-delay circuits with active devices (Gunn diodes) of relatively simple configurations [10-13]. They were mostly series networks of a few devices with time-delay microstrip coupling or single-diode systems with time-delay feedback where complicated dynamics of high-frequency radiation field have been predicted [10-13].

Here we consider another system, which is a parallel time-delay network of active devices as shown in Fig. 1, a. All active blocks in this network $(n=1,...N)$ are identical, being of the kind shown in Fig. 1, b. A common passive block (n=0) is of the kind shown in Fig. 1, c. The block operates as a remote resonator for the given set of active devices and, in the same time, as a resonant antenna that transmits electromagnetic radiation into an open (infinite) section of microstrip line as shown in Fig. 1, a.

Microstrip lines of length d_n and d_{S_n} provide time-delay coupling and feedback in this system. They are supposed to be sufficiently long as compared to characteristic wavelength of emerging radiation.

Formulation of the problem is provided by the set of equations consisting of

– the wave equations for the current $i_n(\tau,x)$ and voltage $e_n(\tau,x)$ in each section of the microstrip transmission line;

– the circuit equations for each circuit n written in terms of the current $i_n(\tau)$ and voltage $e_n(\tau)$ defined appropriately for each circuit as shown in Figs. 1 (e.g. for active circuits the circuit currents and voltages are

$$i_n = i_n^- = i_n^+, \quad e_n = e_n^- - e_n^+,$$

$$i_n = i_{L_n} = i_{G_n} + i_{C_n}, \quad e_n = e_{C_n} + e_{L_n} - e_{B_n});$$

– the boundary conditions for the wave equations at the points of microstrip connections to the circuits $(x_n^{\pm} = x_n \pm 0)$ which establish the link between the microstrip currents and voltages at the points $x_n^{\pm}$ $(i_n^{\pm}(\tau) = i_n(\tau, x_n^{\pm})$, $e_n^{\pm}(\tau) = e_n(\tau, x_n^{\pm}))$ and the circuit currents and voltages $i_n(\tau)$, $e_n(\tau)$ as shown in Fig. 1.

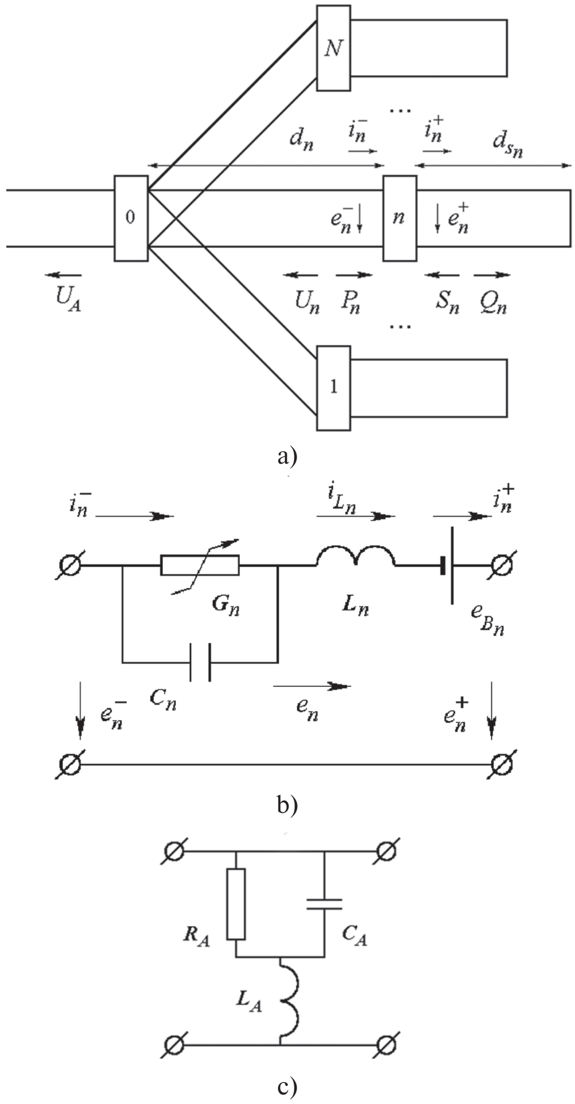


Fig. 1. (a) A network of active circuits connected by sections of microstrip transmission lines and schematics of (b) active circuits used in the network and (c) a resonant circuit used as an antenna node $n = 0$

The set of equations is completed by the radiation condition at $x = -\infty$ (no incoming waves from the open end of the transmission line) and the short-circuit condition that leads to the occurrence of reflected waves from the ends of the stub sections d_{S_n}.

Despite apparent simplicity of circuits considered, self-consistent time-domain modelling of these distributed systems is a complicated problem.

In case of a small spatial dispersion of microstrip line the linear part of the problem is simplified significantly so as the wave propagation in the waveguide sections is described by a well-known Riemann-D'Alembert solution to the one-dimensional wave equation. In our modelling, we use this approach for time-domain simulation of linear part of the problem while the nonlinear part is modelled in full, in distinction from a more traditional approach. It allows us to reduce the problem described with complicated partial differential equations to a problem with an equivalent set of ordinary differential-difference equations with time delay (the equations with deviating argument).

Despite the remaining complexity caused by delay, the equations can be solved by available numerical methods [15]. In the explicit form, differential-difference equations for electromagnetic waves in a network of transmission lines with active blocks ($n=1...N$) described above are presented as follows:

$$\begin{gathered} U''_n(\vartheta_n) = -P''_n(\vartheta_n - d_n) + \\ +\omega_{L_n} e'_{B_n}(\tau) + 2\omega_{L_n}[S'_n(\vartheta_n - 2d_{S_n}) - \\ -U'_n(\vartheta_n)] - \omega_{0_n}^2 [U_n(\vartheta_n) + P_n(\vartheta_n - d_n) - G_n(e_{C_n})], \end{gathered} \quad (1)$$

where

$$P_n(\vartheta_n - d_n) = U_n(\vartheta_n - 2d_n) - e_{C_A}(\tau - d_n) - U_A(\tau - d_n); \quad (2)$$

$$S_n(\vartheta_n) = U_n(\vartheta_n) + P_n(\vartheta_n - d_n) - S_n(\vartheta_n - 2d_{S_n}); \quad (3)$$

$$\begin{gathered} e_{G_n} = e_{B_n} + 2[S_n(\vartheta_n - 2d_n) - U_n(\vartheta_n)] - \\ -\tau_{L_n}[U'_n(\vartheta_n) + P'_n(\vartheta_n - d_n)]. \end{gathered} \quad (4)$$

In these equations, $U_n(\vartheta_n)$, $P_n(\vartheta_n)$, $Q_n(\vartheta_n)$, $S_n(\vartheta_n)$ and $U_A(\tau)$ are the amplitudes of the waves propagating in the corresponding sections of the line (Fig. 1a) presented as functions of time variables $\vartheta_n = \tau + d_n = \tau + x_n$, $\vartheta_{S_n} = \vartheta_n + d_{S_n} = \tau + x_{S_n}$ and the current time τ in such a manner that

$$\begin{gathered} i_n^+(\tau) = S_n(\vartheta - 2d_{S_n}) + S_n(\vartheta_n), \\ e_n^+(\tau) = -S_n(\vartheta - 2d_{S_n}) + S_n(\vartheta_n), \\ i_n^-(\tau) = U_n(\vartheta_n) + P_n(\vartheta_n - d_n), \\ e_n^-(\tau) = -U_n(\vartheta_n) + P_n(\vartheta_n - d_n), \\ i_{A_n}^+(\tau) = U_n(\vartheta_n - d_n) + P_n(\vartheta_n), \\ e_{A_n}^+(\tau) = -U_n(\vartheta_n - d_n) + P_n(\vartheta_n), \\ i_A^-(\tau) = U_A(\tau), \\ e_A^-(\tau) = -U_A(\tau). \end{gathered} \quad (5)$$

The index A designates the variables associated with the antenna element (see designations on Figs. 1a, 1c), and the value $U_A(\tau)$ describes the wave radiated into the open section of TL towards the infinity.

Notice that all the equations in this work are written in terms of dimensionless normalized variables such as the relative coordinate $x = X/a$, , time $\tau = ct/a$, , voltage $e_n = V_n/V_0$ and current $i_n = Z_0 I_n / V_0$, where a is the spatial scale used for normalization, c is the speed of wave in the transmission line, Z_0 is the intrinsic impedance of the line, V_0 is the normalization voltage. In a similar way, we introduce other dimensionless parameters such as $\tau_{C_n} = cZ_0 C_n / a$, $\tau_{L_n} = cL_n/(Z_0 a)$, $\tau_{0_n} = 2\pi(\tau_{L_n}\tau_{C_n})^{1/2}$, $\omega_{C_n} = 1/\tau_{C_n}$, $\omega_{L_n} = 1/\tau_{L_n}$ and $\omega_{0_n} = (\omega_{L_n}\omega_{C_n})^{1/2}$, etc.

The Gunn diodes are simulated in terms of the given current-voltage characteristics with negative differential resistance (NDR) as shown in Fig.2. This approximation assumes the limited space-charge accumulation (LSA) mode of operation of Gunn diodes. This allows a rather broadband functioning of the devices, with the maximum-to-minimum frequency ratio exceeding a decade. The approximation means an instant response of the diodes to the external field neglecting the modelling of strong-field domains in the diode structures. Instead, characteristic times of intrinsic processes specific for the diodes are represented by the equivalent capacitance C_n and the inductance L_n of the devices and their connections to the circuits. The current-voltage characteristic of the diodes is given by the approximation [16] typical for GaAs and GaN structures

$$G_n = G_n(e) = G_{0_n}[(e + 0.2e^4)/(1 + 0.2e^4) + 0.05e], \quad (6)$$

where $G_{0_n} = Z_0 I_{0_n} / V_0$ is the dimensionless diode current parameter, I_0 and V_0 are the characteristic absolute current and voltage specifying the diodes (e.g., for the L-band GaN THz Gunn diodes described in [17], we have $I_0 \approx 8A$, $V_0 \approx 30V$), and, finally, $e = |e_{G_n}|$ is the dimensionless voltage applied to the diode (Fig.2).

The model of this kind became an engineering norm for the time-domain calculations and applied, for example, in the well-known circuit design software *HSPICE*.

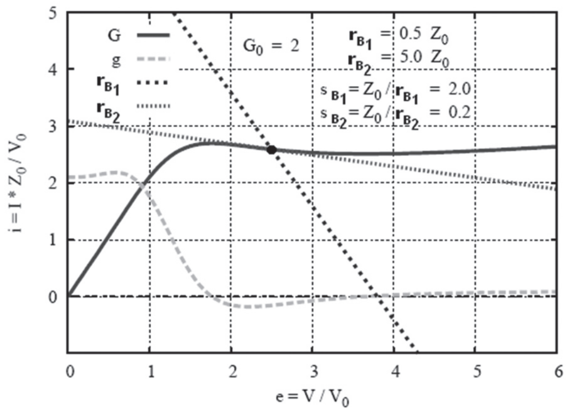


Fig. 2. The Gunn diode current-voltage characteristic $G_n = G_n(e)$, $g_n(e) = dG_n(e)/de$ — the differential conductance, and the load lines at the bias resistance r_B

The electromagnetic self-excitation appears in the system when the Gunn diodes are biased to the NDR region. The oscillations develop in response to a small fluctuation of the bias voltage, once the voltage is in this region, or as a result of switching the bias from the stable to this unstable domain.

The bias voltage $e_B(\tau)$ is specified by the function

$$e_B(\tau) = e_{B_0} + \delta e_B f_B(\tau/\tau_S) - \delta e_B f_B((\tau - \tau_F)/\tau_S),$$

where e_{B_0} is the steady-state voltage in the "off" position below the threshold $e_{B_{th}}$ when no self-oscillations are excited (the oscillations appear if $e_B > e_{B_{th}}$), $e_{B_1} = e_{B_0} + \delta e_B$ is the steady-state voltage in the "on" position when self-oscillations are being developed ($e_{B_1} > e_{B_{th}}$), $f_B(\tau/\tau_S)$ is the bias switch function which describes the switching on and off process beginning at the moment $\tau = 0$ and $\tau = \tau_F$, respectively, and developing during the characteristic time τ_S ($0 \le f_B \le 1$, $f_B = 0$ at $\tau \le 0$, $f_B = 1$ at $\tau \ge \tau_S$).

As a switch function, we choose $f_B = (\tanh(u) + 1)/2$, with the substitution $u = s/(1 - s^2)$, $s = 2\tau/\tau_S - 1$, defined in the interval

$|s|<1$ where $0 \le f_B \le 1$ ($f_B = 0$ at $s = -1$, $f_B = 1$ at $s = 1$), while outside of this interval we assign $f_B = 0$ at $s < -1$ ($\tau < 0$) and $f_B = 1$ at $s > 1$ ($\tau > \tau_S$).

This definition of the switch function f_B allows us to confine the duration of switching on and off within the finite time interval $0 \le \tau \le \tau_S$, with both $df_B / d\tau$ and $d^2 f_B / d\tau^2$ being zero at $\tau \le 0$ and $\tau \ge \tau_S$. Notice, the condition $df_B / d\tau = d^2 f_B / d\tau^2 = 0$ at $\tau \le 0$ is necessary for the consistency of time-delay equations at $\tau \le 0$ with the trivial initial conditions on the unknown functions at the time-delayed intervals while assuming no time variations before the switching on begins.

In a similar way, we write the equations for the resonant antenna circuit ($n = 0$) schematically shown in Fig. 1, a and c. As a result, we obtain a complete system of $N+1$ second-order differential-difference equations, which describe the electromagnetic field evolution in the given microwave circuit of transmission lines with active Gunn-diode devices. They account for both the nonlinearity of devices and the delay of coupling between the devices due to the time needed for the wave propagation along the transmission lines. This property makes the system prone to non-conventional dynamics such as the dynamical chaos and other nonlinear effects that could be useful for various applications.

3. NUMERICAL REZULTS

We obtain numerical solutions of the equations in by using the integration methods presented in [15], particularly, the Dormand-Prince method of the 8(5+3) order, which we extended for the case of time-delay equations specific for our problem. Being direct time-domain computations, accurate solutions of these nonlinear equations are rather time-consuming. Time sequences of the field evolution were, typically, found for many thousands of intrinsic periods T_n as defined by the system parameters, with the accuracy of solutions specified at the level $\varepsilon = 10^{-7}...10^{-12}$ [15] sufficient for obtaining stable and reproducible solutions as verified by more accurate test simulations.

When considering a network with a single active circuit ($N = 1$), we found a possibility for the system to generate a train of high-frequency pulses radiated into an open section of microstrip line (Fig. 3). The pulses are excited when the bias voltage E_{B_n} is increased above a threshold value (the system is turned on) and cease when E_{B_n} is reduced below the threshold.

A characteristic feature of the effect is that the pulse duration t_P equals to the time interval between the pulses Δt_P and each of them is close to the duration of the round trip of a signal from the active device ($n = 1$) to the remote resonator ($n = 0$) and back to the active device ($n = 1$). Thus, the spatial length of each pulse in an infinite microstrip line $L_p = ct_p$ (c is the speed of wave in the line) is about twice the length of the microstrip section, $L_p = 2d_n$.

The carrier frequency of each pulse ω is determined by the intrinsic frequency of active circuits, and the optimal condition for the formation of a clear sequence of pulses is the coincidence of intrinsic frequencies of the remote resonator ($n = 0$) and the active circuit ($n = 1$), while the length of microstrip section d_n that provides a time-delay coupling is required to be large enough for the pulse duration t_p to be much greater than the oscillation period $\tau = 2\pi\omega$.

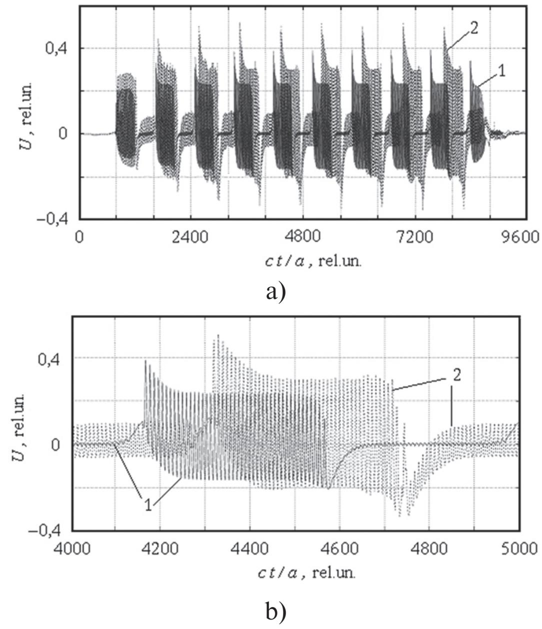


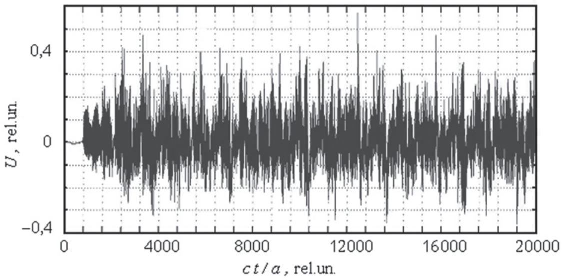
Fig. 3. A train of high-frequency pulses radiated from the system of one Gunn-diode active circuit (curves 1) and two identical active circuits (curves 2) when the circuits are connected to the antenna node $n = 0$ by microstrip transmission lines of length $d_n = 200$ (in relative units where the pulse radiation wavelength is $\lambda = 9.0$)

The formation of train of pulses and the main conditions for this could be explained as follows. If the active circuit is designed so that oscillations are excited when no resonator is present at the antenna node n=0, the oscillations arise and exist for the duration of time t_P until the feedback signal returns from the remote resonator ($n = 0$) to the active node ($n = 1$). Then, if the design of the entire system including both the active circuit and the remote resonator is of such a kind that oscillations cannot exist in the entire system, the oscillations cease for the period of time Δt_p when active circuit receives a feedback from the node $n = 0$ and, in this way, "feels" the presence of remote resonator. After that time, the feedback disappears, the active circuit does not "feel" any remote resonator again, and a new pulse of oscillations arises.

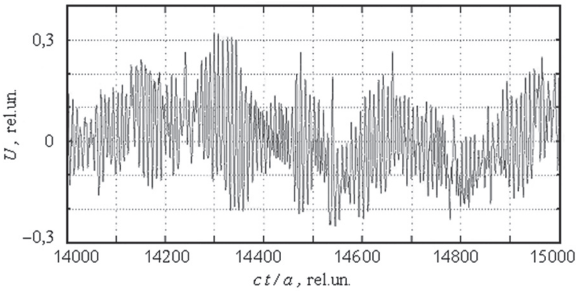
When connecting two identical branches of active circuits in parallel to the antenna node, we obtain a similar train of pulses radiated from the system, though of slightly different parameters (Fig. 3, b). With increasing the number of branches, the oscillations may not cease completely between the pulses and the entire process becomes more complicated.

Keeping in mind the explanation of the effect given above, we may consider the networks of multiple time-delay branches of different length of microstrip sections. With account of different times of arriving time-delay feedbacks from different circuits and nonlinear mixing of oscillations in active devices, we can expect the development of complicated and, potentially, chaotic or quasi-chaotic oscillations that could be of interest for certain applications [14].

Consider now the network of two branches of identical active circuits of the kind shown in Fig. 1, though of different and, preferably, non-commensurable length of time-delay microstrip sections d_n .



a)



b)

Fig. 4. A quasi-chaotic signal radiated from a system of two active circuits connected to the antenna node by transmission lines of length $d_1 = 200$ and $d_2 = 266.67$, respectively, when the basic radiation wavelength at the emerging carrier frequency is $\lambda = 8.6$

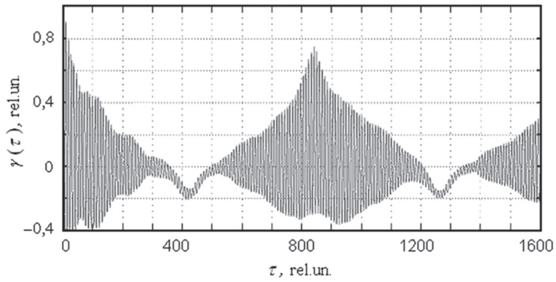
In this case, despite the relative simplicity of active system, there will be a complicated mixing of time-delay feedbacks in different branches of active devices, thus, providing a complicated (virtually, quasi-chaotic in the lower frequency bands) nonlinear oscillations as shown, e.g., in Fig. 4 (a similar effect should also arise in the networks of dispersive transmission lines because of different propagation time of different frequency components).

In this example, even though there is a certain carrier frequency due to intrinsic oscillations of active circuits, the entire waveform that corresponds to the lower frequency band as compared to the carrier frequency, is rather chaotic and remains so for a long period of time being simulated (here we choose the length parameters $d_1 = 200$ and $d_2 = 266.67$ in relative units, while the carrier oscillation period is $\tau = 8.6$.

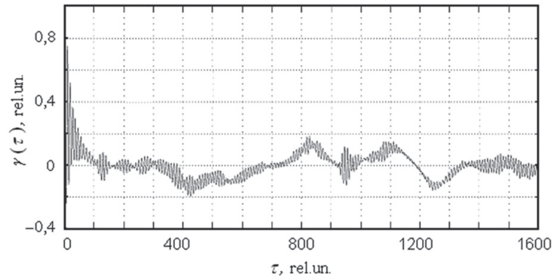
Quasi-chaotic character of low-pass-band signal radiated from the system is well illustrated by the plots of auto-correlation function and Poincare section computed for the emerging oscillations (Figs. 5–6).

When comparing auto-correlation functions (Fig. 5) of train of pulses and quasi-chaotic signal, one can see a reversal of correlation over the period of pulse repetition (at $\tau \sim 840$ in Fig. 5) and a significant loss of correlation in quasi-chaotic signal at all times exceeding the period of oscillations ($\tau = 8.6$).

In a similar way, Poincare sections (Fig. 6) clearly show the presence of periodicity in the train of pulses over a long period of time and the lack of long-term periodicity in quasi-chaotic signal of Fig. 4. The frequency spectrum of the quasi-chaotic signal is shown in Fig. 7.

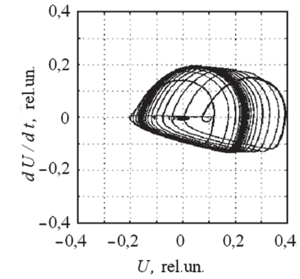


a)

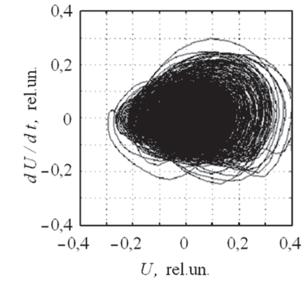


b)

Fig. 5. Auto-correlation function of (a) train of pulses of Fig. 3 and (b) quasi-chaotic signal of Fig. 4 computed over the time interval $t = 1000 - 9000$ and $t = 2000 - 20000$, respectively



a)



б)

Fig. 6. Poincare section U vs dU / dt of (a) train of pulses of Fig. 3 and (b) quasi-chaotic signal of Fig. 4 computed over the time interval $t = 4000 - 8000$

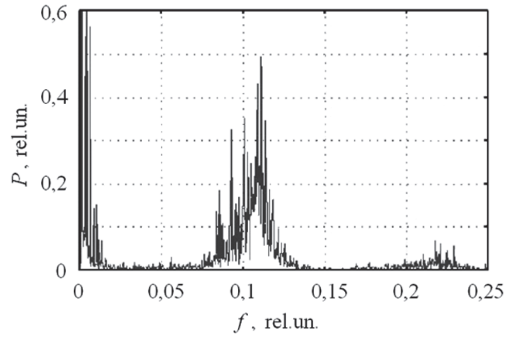


Fig.7. Frequency waveform radiated from time-delay TL circuit ($N = 2$) with $d_n \gg 1$

4. CONCLUSIONS

Time-domain simulations of distributed networks of active circuits connected by sections of microstrip transmission lines have shown a possibility of generation of trains of high-frequency pulses radiated into an open section of transmission line. The trains of pulses can emerge when active devices are separated from compact resonant circuits by extended sections of transmission lines providing a time-delay feedback. When using a few branches of active circuits with different length of time-delay transmission lines, a complicated quasi-chaotic signal can be generated by the system that could be of interest for emerging applications.

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Моделирование во временной области колебаний высокочастотных импульсов в микрополосковых линиях задержки с диодами Ганна / Л.В. Юрченко, В.Б. Юрченко // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 45–50.

В статье было выполнено моделирование во временной области активных систем с диодами Ганна, соединенных секциями микрополосковой линии передачи. Было исследовано самовозбуждение диодов Ганна, вмонтированных различными способами в цепь линии передачи. Обнаружена сложная динамика электромагнитного поля, излученного в открытую секцию микрополосковой линии. Показана возможность появления серии высокочастотных импульсов в случае, когда активные блоки отделены от компактных резонансных элементов протяженными секциями линии передачи с задержкой обратной связи.

Ключевые слова: высокочастотные импульсы, диод Ганна, линии задержки, система с запаздыванием.

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Моделювання у часовому просторі коливань високочастотних імпульсів у мікросмуговій лінії затримки з діодами Ганна / Л.В. Юрченко, В.Б. Юрченко // Прикладна радіоелектроніка: наук.-техн. журнал. – 2013. – Том 12. – № 1. – С. 45–50.

У статті було виконано моделювання у часовому просторі активних систем з діодами Ганна, з'єднаних секціями мікросмугової лінії передачі. Було досліджено самозбудження діодів Ганна, вмонтованих різним чином у ланцюжок лінії передачі. Знайдена складна динаміка електромагнітного поля, що випромінюється у відкриту секцію мікросмугової лінії. Показана можливість появи серії високочастотних імпульсів у випадку, коли активні блоки відділені від компактних резонансних елементів подовженими секціями лінії передачі з затримкою зворотного зв'язку.

Ключові слова: високочастотні імпульси, діод Ганна, лінія затримки, система з запізнюванням.

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