

MODEL SYNTHESIS OF ENERGY COMPRESSORS

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A complete electrodynamic model and a synthesis algorithm of energy compressors have been developed for the first time. The theoretical problems have been solved that occur when constructing these structures on the basis of two connected in series axially-symmetrical open waveguide resonators ('storage + switch'). Figs. 8. Ref.: 18 titles.

Key words: energy compressor, open resonator, waveguide, synthesis.

Microwave energy compressors (see, for example, [1–4]) contain, as a rule, two resonant units: one of them is meant for accumulating an input energy, while another plays the role of a switch, which closes the output section at the time of energy accumulation and opens it at the moment of discharge. The optimal matching of these units is rather complicated electrodynamic problem. Its solution has to provide the following:

- coincidence (adjacency) of the operating (resonance) frequencies $\text{Re}k_A$ and $\text{Re}k_L$ of the storage volume and the switch;
- required dynamics and the limits of the field intensity growth for operating oscillations in the storage resonator and in the switch (both are determined by the Q-factors of the oscillations in the corresponding open or closed resonators, namely, by the values $\text{Im}k_A$ and $\text{Im}k_L$, by a deviation of the central frequency k_c of a quasi-monochromatic exciting pulse from compressor's operating frequency k_w , and by parameters of a coupling window between the feed line and the storage volume);
- the possibility of fast discharge (the eigenfrequencies k_{LA} of the system 'unlocked storage volume' may not be located in the vicinity of k_w in the complex plane of variable k).

It is evident that all basic characteristics of the open system 'feed waveguide–coupling window–storage–switch–output waveguide' are interrelated parameters. Variations in any of them cause changes whose effect cannot be estimated simply experimentally, in the context of simplified, approximate models, although these changes can deteriorate essentially the system characteristics. The computational experiment based on a rigorous mathematical simulation offers evident advantages

over the traditional approaches to the synthesis of the devices of this kind. It simplifies the optimization of the synthesized structures allowing one to examine efficiently a lot of options [5] and to analyze in detail the physical processes taking place in compressors.

1. Simulation and Analysis, Model Synthesis. One section in [6] is devoted to the development of the general approach to solving problems of model synthesis of resonant quasi-optical devices. As applied to microwave energy compressors, this approach has been implemented for the first time in [7]. It includes: estimation of a range of functional capabilities of separate elements and matching of these capabilities with the functional area of the unit as a whole; construction of the mathematical model of the unit and its electrodynamic analysis. For solving the problems arising at these stages (as a rule, these are open boundary-value or initial boundary-value problems, i.e. the problems with infinite analysis domain along one or several axes) we use the rather powerful and universal time-domain methods [8]. These algorithms supplied with the original 'fully absorbing' boundary conditions [5,9,10] allows one to carry out the analysis in bounded spatial domains for any time intervals and to obtain reliable numerical data describing transient processes under resonant conditions. It should be noted that the well-known heuristic and approximate algorithms truncating a computational domain, which are based mainly on the application of the Absorbing Boundary Conditions [11,12] and Perfectly Matched Layers [13] (occurring in practically all widespread software packets for electrodynamics) don't assure correct results in the case of resonant wave scattering.

The developed algorithms have been implemented in the packets of special-purpose computer programs for simulation and analysis of energy compressors and resonant radiators of high-power short radio pulses with arbitrary types of storage units (waveguide and open resonators with metal, semitransparent, and frequency-selective

mirrors) and switches (distributed grating-type switches for compressors on multimode waveguides and for resonant radiators; interference and resonant switches for compressors with single-mode output waveguides).

Although compressors are various in constructions and hence the development of separate details during the analysis and synthesis procedures requires an individual approach, all basic stages of the scheme presented below are implementable in many practically interesting cases.

Consider a synthesis problem of axially-symmetrical ($\partial/\partial\phi \equiv 0$) direct-flow compressors on the sections of circular and coaxial circular waveguides with the single-mode input and output ports on TM_{01} - and TEM -waves, respectively. The wall loss is neglected. The compressor characteristics obtained (the degree of compression, i.e. a ratio between input and output pulse durations; the efficiency, i.e. a ratio between the energy stored in the output and input pulses; the power gain, i.e. a product of the degree of compression and the efficiency) are not optimal. At this stage, it was important to develop a synthesis algorithm proper, in other words, to formulate the theoretical problems that occur when constructing compressors and to determine the methods of solution.

In the paper, the SI system of units is used. The variable t is the product of the real time by the velocity of light in free space and has the dimensions of length. We drop all dimensions. In the analysis that follow, $k = 2\pi/\lambda$ is the wavenumber (a frequency parameter or a frequency), λ is the wavelength in free space, ε and σ_0 are the relative permittivity and specific conductivity; ρ , ϕ , z are the cylindrical coordinates, $\vec{E} = \{E_\rho, E_\phi, E_z\}$ and $\vec{H} = \{H_\rho, H_\phi, H_z\}$ are the electric and magnetic field vectors, $g = \{\rho, z\}$ is a point in the two-dimensional space, L_j are the virtual boundaries of the computational domain Q_L , S is the boundary of the perfectly conducting parts of the compressor; $v_n^\rho(z, t)$ are the space-time amplitudes of E_ρ -components of pulsed waves. The geometrical parameters in the model problems under consideration are given in meters, however, all the results obtained here can be easily recalculated for other geometrically similar structures.

2. Algorithm of the Model Synthesis of an Energy Compressor. The frequency properties of the open or closed resonator considered as an accumulator of energy can be determined by the time-domain methods from the response of this resonator on the excitation by a broadband signal

[5,14,15]. Let, at first, the pulsed TM_{01} -wave $U^i(g, t)$ with the amplitude of E_ρ -component

$$v_1^\rho(0, t) = 4 \frac{\sin(\Delta k(t - T_0))}{(t - T_0)} \cos(k_c(t - T_0)) \chi(T - t) = F_1(t)$$

excites a storage unit with the closed (Fig. 1, a) and open (Fig. 1, b) output channel. The central frequency of the signal $U^i(g, t)$ is $k_c = 3,4$; parameters $\Delta k = 1,1$, $T_0 = 30$, and $T = 400$ determine its spectral band ($2,3 < k < 4,5$), a delay time (a moment of time at which the principal part of the pulse crosses the virtual boundary L_1 in the plane $z = 0$ of a cross-section of the input waveguide),

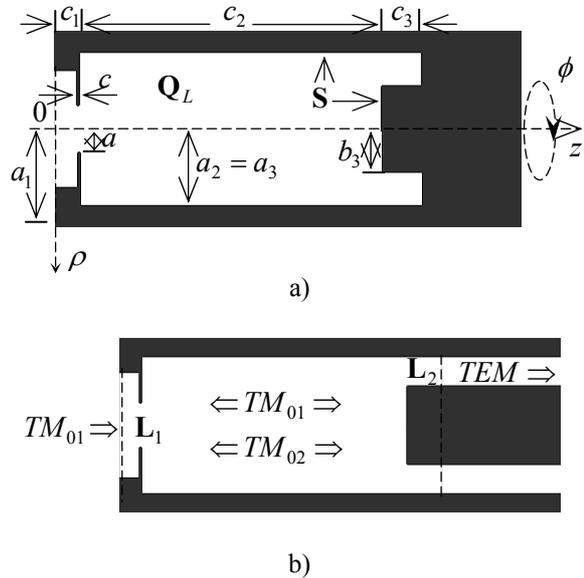


Fig. 1. Geometry of the storage volume with the feeding waveguide, closed (a) and open (b) output channels; $a = 0,5$, $c = 0,06$

and the duration or the observation time T (χ is the Heaviside step-function). In the frequency range $2,3 < k < 4,5$, the spectral amplitudes of the E_ρ -component of this wave (or of the wave $U^i(g, t)$): $v_1^\rho(0, t) = F_1(t)$; $k_c = 3,4$, $\Delta k = 1,1$, $T_0 = 30$, and $T = 400$) are close to unity ($|v_1^\rho(0, k)| \approx 1$; from here on $\bar{f}(k)$ stands for the Fourier transform of the function $f(t)$). In the input circular waveguide ($a_1 = 1,2$, $c_1 = 0,5$) and in the output coaxial circular waveguide ($a_3 = 1,56$, $b_3 = 0,9$, $c_3 = 0,8$)

only principal TM_{01} - and TEM -waves propagate over the frequency range considered. In the central circular waveguide (in the storage unit, $a_2 = 1,56$ and $c_2 = 6,0$), initially only TM_{01} -wave is propagating (up to the frequency $k \approx 3,53$), and then TM_{02} -wave arises. A beyond-cutoff aperture ($k < 4,8$) separates the input waveguide and the storage.

Approximate values for real parts of complex eigen frequencies k_A of the storage with the locked output waveguide can be determined from the dynamics in variation of $\arg R_\phi^{11}(k)$, where $R_\phi^{11}(k)$ is the conversion factor of the incident TM_{01} -wave into the wave reflected from the virtual boundary L_1 with respect to H_ϕ -component: in the vicinity of resonant points $\text{Re}k_A$ the dynamic-phase effect [16] is realized. Approximate values for real parts of complex eigen frequencies of the storage with unlocked output channel is determined from the resonance spikes of the curve $|R_\phi^{11}(k)|$. Let us take two values of $\text{Re}k_A$ ($\text{Re}k_A \approx 2,72$ and $\text{Re}k_A \approx 4,17$) from nine values found, one for an oscillation on TM_{01} -wave and another for TM_{02} -wave. This kind of selection is dictated, as a rule, by a synthesis task (the acceptable operation frequency range) and by the requirement of a fast discharge.

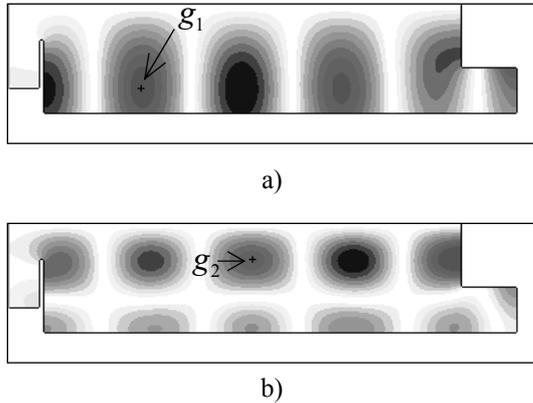


Fig. 2. Spatial distribution of the H_ϕ -components in the freely oscillating fields ($t = 450$) associated with the resonant frequencies $\text{Re}k_A \approx 2,728$ (a) and $\text{Re}k_A \approx 4,172$ (b)

Characteristics of the free oscillations associated with the selected values $\text{Re}k_A$ can be defined more exactly from the response of the storage volume on the excitation by a quasi-monochromatic signal with the central frequency

$k_c = \text{Re}k_A$ [14,15]. For the results presented in Fig. 2, $k_c = 2,72$ (Fig. 2, a) and $k_c = 4,17$ (Fig. 2, b), while parameters of the quasi-monochromatic TM_{01} -wave exciting the storage are given by the function

$$v_1^\rho(0, t) = P(t) \cos k_c(t - T_0) = F_2(t). \quad (1)$$

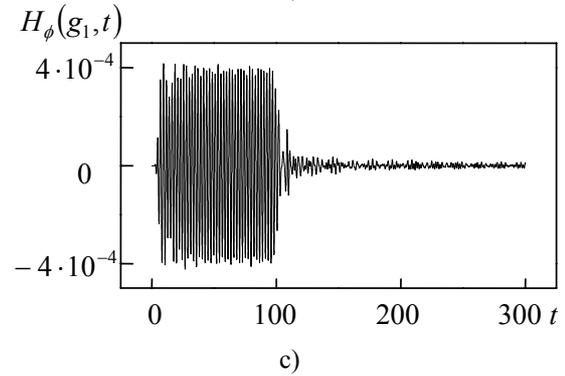
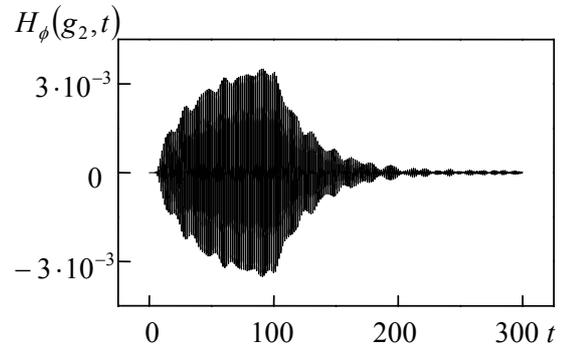
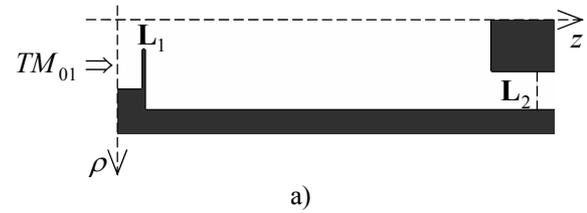


Fig. 3. Time-dependencies of H_ϕ at the points g_1 (b) and g_2 (c) when exciting the storage with an open output channel (a) by a quasi-monochromatic TM_{01} -pulse (the pulse duration is 100) with the central frequency $k_c = 4,172$ (b) and $k_c = 2,728$ (c)

A trapezoidal envelope $P(t)$ of signal (1) ($U^i(g, t): v_1^\rho(0, t) = F_2(t)$, k_c , $T_0 = 0,5$, $T = 500$, $P(t): 0,1 - 5 - 95 - 99,9$) is equal to zero for $t < 0,1$, $t > 99,99$ and to unity for $5 < t < 95$. A freely oscillating field is formed at $t > 100$, when the source is turned off. From spectral amplitudes of the functions $H_\phi(g, t)$ for $t > 100$, at the points

$g = g_1$ and $g = g_2$ corresponding to the antinodes of free oscillations, determine $\text{Re}k_A$ more precisely: $\text{Re}k_A \approx 2,728$ and $\text{Re}k_A \approx 4,172$.

When exciting the storage with the open output channel (Fig. 3) by a quasi-monochromatic wave $U^i(g, t): v_1^\rho(0, t) = F_2(t)$, $k_c = 4,172$, $T_0 = 0,5$, $P(t): 0,1 - 5 - 95 - 99,9$ (TM_{025} -oscillation is excited in the storage volume), the field intensity increases and then (at $t > 100$) decreases gradually (Fig. 3, b). The situation with TM_{015} -oscillation (Fig. 3, c) is much better – this oscillation we choose as the storage operating oscillation.

At the next step, we select a design of the switch, whose attachment to the open port \mathbf{L}_3 (Fig. 4, a) will not change substantially the electrodynamic characteristics of the storage at the frequency $k = \text{Re}k_A \approx 2,728$. As a switch, the slot resonator (see the right-hand part of Fig. 4, a and [17]) has been chosen. This resonator almost completely locks the output coaxial waveguide at $k = 2,728$ (Fig. 4, b). The resonators of this type are easily tunable on the required operating frequency by choosing the slot depth. By varying the slot width, we can control the rate of rise of E_z -component to select the value, which results in a discharge [17].

With the chosen construction (Fig. 5, a), the requirement $|E_\rho(z \in \mathbf{L}_2, \text{Re}k_A)| = 0$ (which ensures electrodynamic equivalency between the storage with the closed output waveguide (Fig. 1, a) and the compressor as a whole (Fig. 5, a)) can be easily satisfied at the frequency $k = \text{Re}k_A \approx 2,728$ by varying the distance between the boundaries \mathbf{L}_2 and \mathbf{L}_3 . For the slot resonator shown in Fig. 4, a, the reflection coefficient for E_ρ -component at $k = 2,728$ is $R_\rho^{00}(k) \approx 0,9961 \exp(-0,673i)$. Under these conditions, the requirement $|E_\rho(z \in \mathbf{L}_2, \text{Re}k_A)| = 0$ can be replaced by the following: the argument of the reflection coefficient R_ρ^{00} , being translated onto the boundary \mathbf{L}_2 , must be equal to $\pm \pi$ [18]. This requirement can be satisfied by placing between the boundaries \mathbf{L}_2 and \mathbf{L}_3 a section of a regular coaxial waveguide of length

$$l = \frac{\pm \pi - \arg R_\rho^{00}(\text{Re}k_A)}{2 \text{Re}k_A} = (\pm \pi + 0,6731) / 2 \cdot 2,728 = \begin{cases} +0,7 \\ -0,45 \end{cases} \quad (2)$$

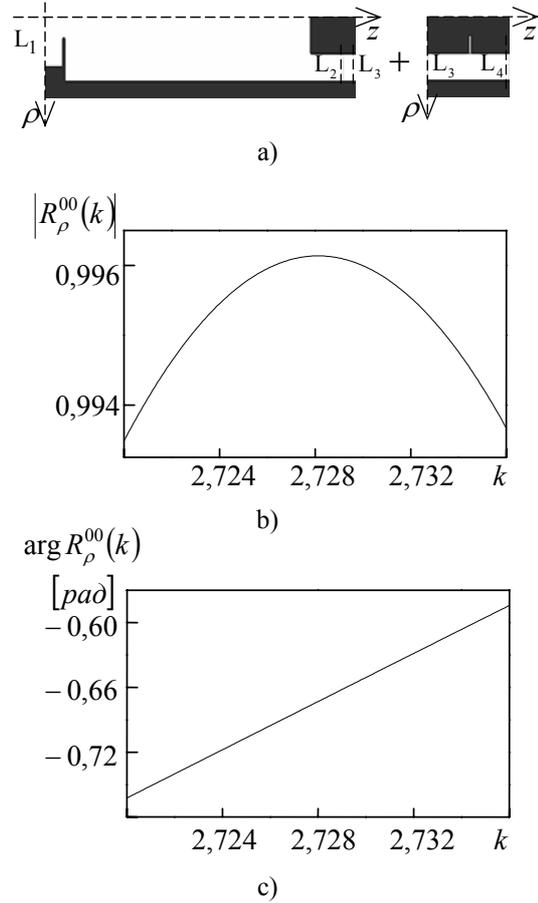


Fig. 4. Synthesis of the compressor switch: geometry (a), the absolute value (b) and the phase (c) of the transformation coefficient (with respect to the E_ρ -component) of the incident TEM -wave into the reflected wave on the virtual boundary \mathbf{L}_3 in the vicinity of the resonant frequency of the storage $\text{Re}k_A \approx 2,728$. The resonator length (the distance between the virtual boundaries \mathbf{L}_3 and \mathbf{L}_4) equals 2,0. A slot 0,44 in depth and 0,06 in width is located to the right of the compressor center and is filled with a stuff of permittivity $\varepsilon = 1,055$

Let us choose in (2) the negative l (the virtual boundary \mathbf{L}_2 is located to the right of \mathbf{L}_3 in the z -axis). In this case, the compressor looks as shown in Fig. 5, a.

The result of the excitation of this structure by a long quasi-monochromatic TM_{01} -pulse $U^i(g, t): v_1^\rho(0, t) = F_2(t)$, $k_c = 2,728$, $T_0 = 0,5$,

$T = 2000$, $P(t): 0,1-5-1995-1999,9$ is presented in Fig. 5, b, c. The field in the locked storage is practically the same as in the storage with the closed output channel (see Fig. 2, a). E_ρ -component, as required, becomes zero on the virtual boundary L_2 , which coincides with the closed end of the coaxial waveguide in the storage resonator.

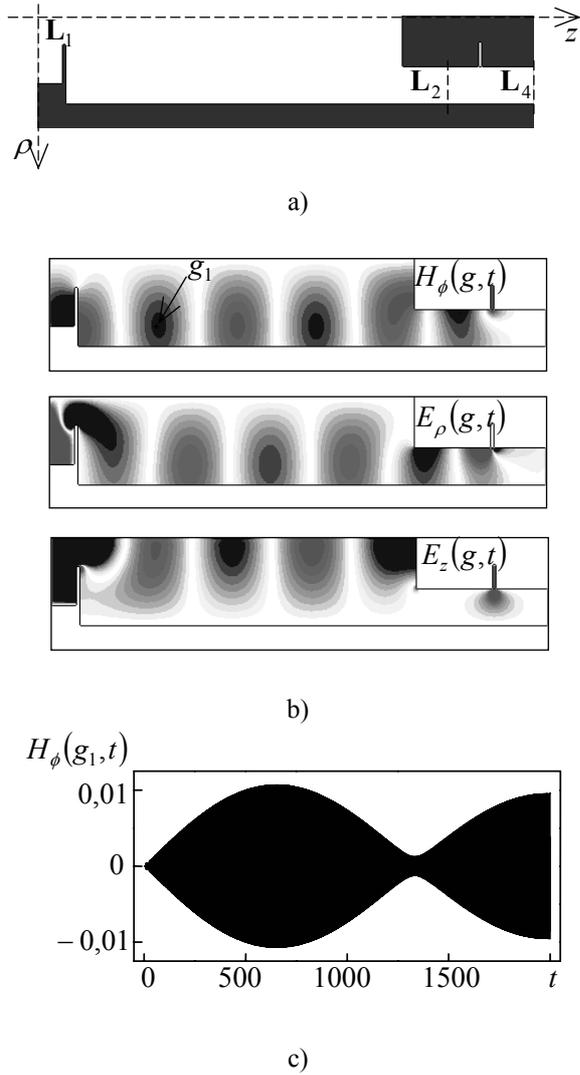


Fig. 5. Geometry (a) and electrodynamic characteristics (b,c) of the compressor when exciting it by a long quasi-monochromatic TM_{01} -pulse with the central frequency $k_c = 2,728$: (b) – spatial distribution of the field components at $t = 1000$, (c) – H_ϕ -component at the point $g = g_1$

However, the behavior of the function $H_\phi(g, t)$ at the point $g = g_1$ is inconsistent with the expected: instead of the regular accumulation of the energy we have beat, whose periodicity indicates that the operating frequency has deviated, even if very

slightly, from the estimated value. Excite the compressor by the TM_{01} -pulse $U^i(g, t): v_1^\rho(0, t) = F_2(t)$, $k_c = 2,728$, $T_0 = 0,5$, $T = 2000$, $P(t): 0,1-5-595-599,9$ and determine from the spectral amplitudes of $H_\phi(g_1, t)$ -component of the free-oscillating field (for $t > 600$) a new value of the operating frequency $k_w = 2,723$ (the operating wavelength is $\lambda_w \approx 2,31$).

3. Results of the Model Synthesis. At the frequency $k = k_w$, the absolute value of the reflection coefficient $R_\rho^{00}(k)$ in the slot resonator equals 0,9952, it is less than the value $|R_\rho^{00}(k)|_{k=2,278} = 0,9961$ used in the synthesis of the switch. Hence, when analyzing parameters of the synthesized compressor, there is a need to determine, first of all, the spectral characteristics of the open resonant system ‘feed waveguide – coupling window – storage – switch in its charging phase’, namely, the complex eigenfrequency K_{LA} and the field configuration of the corresponding free oscillation.

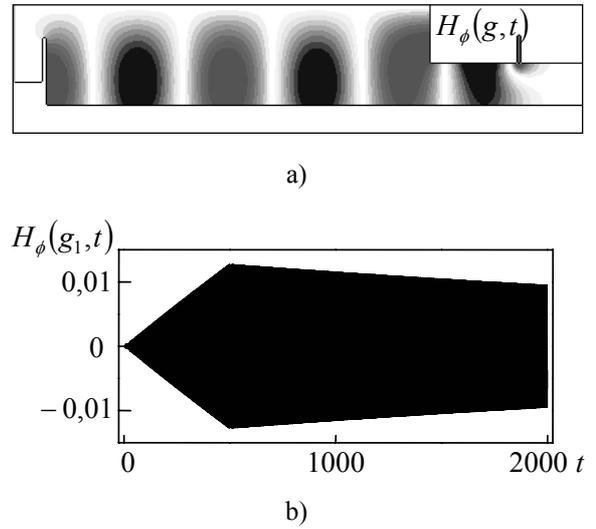


Fig. 6. To the determination of spectral characteristics of the open system ‘feeding waveguide – coupling window – storage volume – switch in its charging phase’: H_ϕ -component of a freely (for $t > 500$) oscillating field at $t = 1000$, (b) – $H_\phi(g, t)$ at the point $g = g_1$. The compressor is excited by a TM_{01} -pulse $U^i(g, t): v_1^\rho(0, t) = F_2(t)$; $k_c = 2,723$, $T_0 = 0,5$, $T = 2000$, $P(t): 0,1-5-495-499,9$

It is evident that $\text{Re}K_{LA} \approx k_w$, while the freely oscillating field (Fig. 6, a) repeats in outline the

forced oscillations presented in Fig. 5, b. From the behavior of the function $H_\phi(g_1, t)$ (see Fig. 6, b) on the interval $500 < t < 2000$ (where the field oscillates freely) determine [15] the value $\text{Im}K_{LA} \approx -1,9 \cdot 10^{-4}$ and the Q-factor of the open system $Q = \text{Re}K_{LA}/2|\text{Im}K_{LA}| \approx 7160$.

Electrodynamic characteristics of the compressor during the charging and discharging phases (excitation by the monochromatic signal $U^i(g, t): v_1^p(0, t) = F_2(t), k_c = 2,723, T_0 = 0,5, T = 4200, P(t): 0,1 - 5 - 4195 - 4199,9$) are shown in Fig. 7 and Fig. 8. The specific conductivity of the material filling the switch slot (Fig. 4, a) is given by the quasi-step time function

$$\sigma_0(t) = \begin{cases} 0; & t \leq 4000 \\ 5,8 \cdot 10^5; & t > 4001 \end{cases}$$

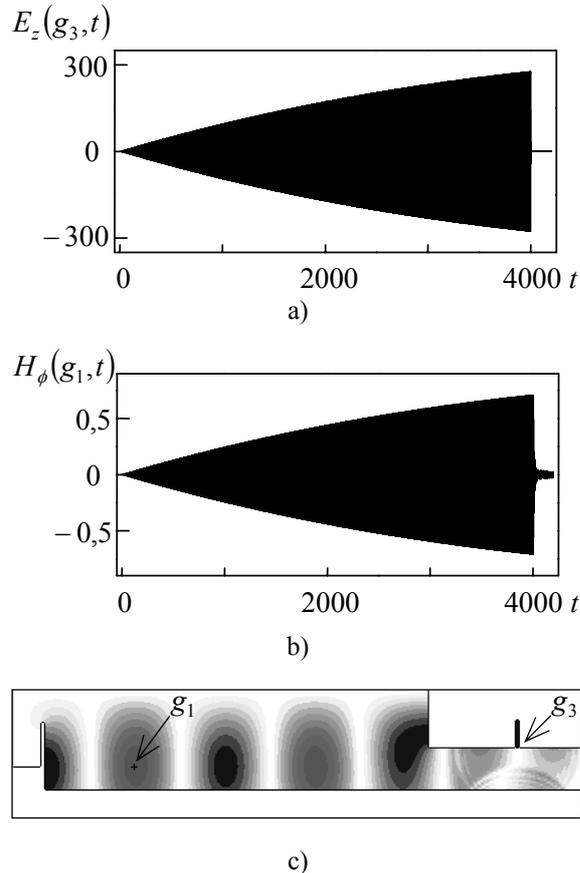


Fig. 7. Growth of the field intensity in the switch (a) and in the storage (b). The spatial distribution of the H_ϕ -component at $t = 4001$ (c) in the discharging phase

When the E_z -component reaches the specified threshold value (Fig. 7, a), the linear increasing function $\sigma_0(t), 4000 < t < 4001$, simulates the

discharge. The discharge transforms a slot resonator into a section of a coaxial waveguide with a weak irregularity (Fig. 7, c).

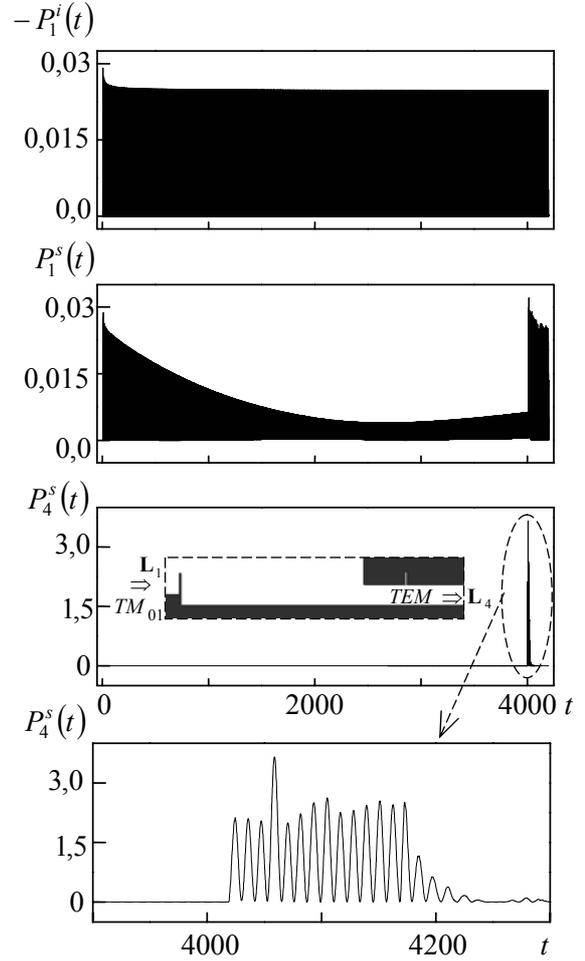


Fig. 8. The instantaneous input power ($-P_1^i(t)$) and radiated power ($P_1^s(t)$ and $P_4^s(t)$) transferred through the virtual boundaries L_1 (feeding circular waveguide) and L_4 (coaxial output)

All accumulated energy is released through the port L_4 in a time equal to twice length of the compressor (see Fig. 8; the distance between the boundaries L_1 and L_4 is 9,8). The efficient duration of the input signal is $T_1^i = 4000$ ($0 < t \leq 4000$), while the duration of the signal resulting from compression is $T_4^s = 21$ ($4002 < t \leq 4023$). By integrating the instantaneous powers $-P_1^i(t)$ and $P_4^s(t)$ over the corresponding time intervals, obtain the following values for the energies accumulated in the input and compressed pulses: $W_1^i \approx 41,19$ and $W_4^s \approx 21,12$.

These data are sufficient for calculating the basic characteristics of the synthesized compressor: the degree of compression $\beta = T_1^i / T_4^s \approx 190$, the efficiency $\eta = W_4^s / W_1^i \approx 0,51$, and the power amplification $\mathcal{G} = \beta\eta \approx 97$.

4. Conclusion. The model synthesis of energy compressors and radiators of high-power short radio pulses is bound to be based on universal and efficient algorithms for solving electrodynamic problems that represent properly the transient processes under resonant conditions. The algorithms of this kind and the packages of specialized computer programs have been developed by the authors and used for the solution of a set of theoretical problems associated with the analysis and synthesis of energy compressors in the form of two axially-symmetrical open waveguide resonators placed in series. The basic stages of the model synthesis are described in detail and supported by numerical results.

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МОДЕЛЬНИЙ СИНТЕЗ КОМПРЕССОРОВ МОЩНОСТИ

И. К. Кузьмичев, П. Н. Мележик, В. Л. Пазынин,
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Разработана и впервые реализована на уровне полной электродинамической модели схема синтеза компрессоров мощности. Найдены решения теоретических задач, возникающих при построении таких устройств на основе двух последовательно соединяемых аксиально-симметричных открытых волноводных резонаторов («накопитель + замок»).

Ключевые слова: компрессор мощности, открытый резонатор, волновод, синтез.

МОДЕЛЬНИЙ СИНТЕЗ КОМПРЕССОРІВ ПОТУЖНОСТІ

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Розроблено та вперше реалізовано на рівні повної електродинамічної моделі схему синтезу компресорів потужності. Знайдено розв'язки теоретичних задач, що виникають під час побудови таких пристроїв на основі двох послідовно поєднаних аксіально-симетричних відкритих хвильоводних резонаторів („накопичувач+замок”).

Ключові слова: компресор потужності, відкритий резонатор, хвильовод, синтез.