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New Methods for Formation and Directed Radiation of Powerful Short Radio Pulses

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Abstract— Fundamentally new schemes for the formation and well-directed radiation of high-power short radio pulses are proposed and analyzed within the framework of the method of exact absorbing conditions. The key feature of these schemes is the implementation of the so-called wave analogs of Smith-Purcell radiation under conditions of the corresponding transformations of electromagnetic waves. But, in the case considered here, the actual radiation is 'delayed' in time for the period when the device operates in the energy storage mode.

1. INTRODUCTION

Model (theoretical) synthesis of devices forming and directionally emitting powerful short radio pulses is based on the consecutive solution of a chain of complex electrodynamic problems associated with: (i) accurate calculation of complex eigen frequencies of storage resonators and resonant switches of device operation modes; (ii) determining the field configuration and Q-factors of free oscillations corresponding to these eigen frequencies; (iii) a reasonable choice of the operating frequency and the study of nonlinear dynamics of energy storage processes in all resonant units of the device; (iv) calculating the instantaneous efficiency of energy storage and determining the point in time when the mode of energy radiation into free space should replace the mode of energy storage; (v) determining the optimal parameters of the 'coupling apertures' at the entrance to the storage cavity and at the exit from it; (vi) the synthesis of emitters with a rather narrow pulse pattern [1], which does not distort the short, powerful radio pulses formed in the storage. Considering the complexity and particularity of the listed problems and our previous experience gained in their consideration [1–7], we can rather soundly state that the method of exact absorbing conditions (EAC-method) [1, 3, 8–13], based on the equivalent replacement of the original open initial-boundary value problems for Maxwell's differential equations with closed problems and its following discretization within the framework of standard computational schemes of the finite difference method [14] or the finite element method [15], is the most suitable for their solution.

In this work, we use the EAC-method to analyze and estimate the efficiency of fundamentally new schemes for the formation and well-directed radiation of high-power short radio pulses. The key feature of these schemes consists in the implementation of the so-called wave analogs of Smith-Purcell radiation [16–19] (their study hade already served as a theoretical basis for the creation of a class of diffractive antennas with unique characteristics [1, 19–26]), provided by the relevant transformations of electromagnetic waves. But, in the case considered here, the actual radiation is 'delayed' in time for the period when the device operates in the energy storage mode.

We use SI, the International System of Units, for all physical parameters except the 'time' t that is the product of the natural time and the velocity of light in vacuum, thus t is measured in meters. In this paper, dimensions are omitted. According to SI, all geometrical parameters (a, b, c, etc.) are given in meters. However, this is obviously not a serious obstacle to extend the results to any other geometrically similar structure.

2. PHYSICAL MODELS

To solve the problem of forming and directed radiation of powerful short radio pulses, two schemes are proposed for consideration. The possibility of their effective implementation is confirmed by the previous experience of the authors and the authentic model and software constructed and 'targeted' to a reliable and complete analysis of such electromagnetic scenarios. The main functional elements of the first scheme and their purpose are as follows. (See Fig. 1):

- The excitation unit is a plane-parallel waveguide A. A long quasi-monochromatic TE_{01}-pulse, whose center frequency coincides with the real part of one of the eigenfrequencies of an open resonator of the length $\bar{l}$, runs from this waveguide through the virtual boundary L^+ on a thin (0.02 thick) diaphragm.
- The open resonator is coupled with the supply waveguide through a beyond cut-off window in a thin diaphragm. Within the chosen excitation method, the free high-Q field oscillations in it are composed by slow counter-propagating waves of a planar dielectric waveguide of the width a, therefore, their spectrum is rather rarefied [7]. When the center frequency of the exciting pulse and the real part of the eigen frequency of the 'operating' free oscillation coincide, the amplitude of these waves increases — the resonator accumulates energy, 'sucking it in' through the beyond cutoff coupling window in a thin diaphragm.
- A planar dielectric waveguide lies on a substrate (it plays the role of lock or switch) with constitutive parameters $\varepsilon_{\text{lock}} = 1.0$ (relative permittivity) and $\sigma_{\text{lock}}(t)$ (conductivity). When operating in the energy storage mode ($0 \leq t \leq t_{\text{accum}} \gg 1$), $\sigma_{\text{lock}}(t) = 5.7 \cdot 10^4$, an almost impenetrable screen separates the planar dielectric waveguide and the grating. When operating in the radiation mode, ($t \geq t_{\text{rad}} = t_{\text{accum}} + 1$), $\sigma_{\text{lock}}(t) = 0$ — the screen disappears and the slow waves composing the operating oscillation begin to 'sweep' the grating, generating the so-called diffraction radiation on one of the spatial harmonics of the periodic structure propagating without attenuation [1, 10, 27–31]. On the interval $t_{\text{accum}} \leq t \leq t_{\text{rad}} = t_{\text{accum}} + 1$, the function $\sigma_{\text{lock}}(t)$ decreases monotonically.
- The grating (its period is equal to $l \ll \bar{l}$) plays a key role in the radiation of powerful short radio pulses. The structure must be symmetric (relatively to certain planes $z = \text{const}$) so that the complex coefficient R characterizing the conversion efficiency of a monochromatic surface wave of a plane waveguide into a propagating spatial harmonic of a periodic grating does not depend on the direction this wave movement — from left to right or from right to left. The harmonic, into which the energy stored in the working free oscillation is transferred, must be directed vertically to the plane of the grating. The modulus of the coefficient R should be large enough at the operating frequency — its value and the magnitude of the aiming distance c determine the speed of accumulated energy radiation into free space, and, consequently, the effective duration of the emitted pulse. Note that all of the listed conditions imposed on the quantity of R can be quite easily satisfied [27–32].
- It should be noted also that the Q-factor of the operating oscillation in the considered resonant system is significantly related to the optimal achievable characteristics of the device [1–7]. It can be changed in a controlled manner by varying the size of the coupling window in a thin diaphragm and the geometry of the main mirrors [1–7].

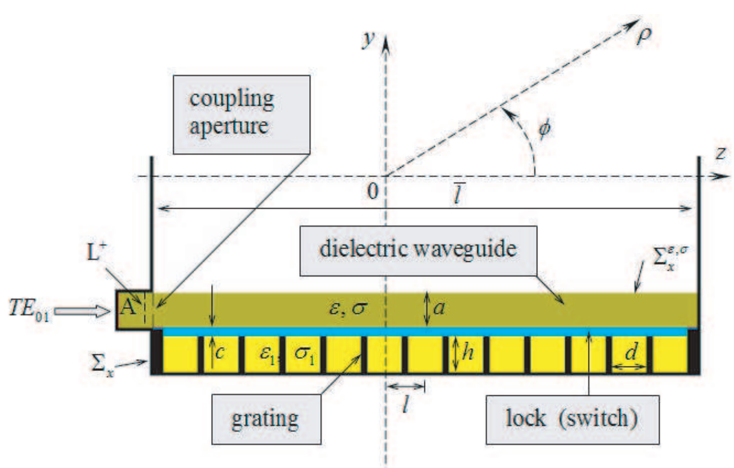

Figure 1: The geometry of the electrodynamic structure implementing the first scheme. Section by plane $x = \text{const}$.

In the geometry of the structure, implementing the second of the proposed schemes (see Fig. 2), we distinguish the following functional elements, which parameters determine the quality of the main electrodynamic characteristics of the device:

- A planar dielectric ($\varepsilon = \text{const} > 1$, $\sigma = 0$) waveguide of a width a supporting the propagation of a surface wave with a frequency-dependent deceleration coefficient $\gamma(k)$ is excited through the virtual boundary L^+ by a TE_{01}-wave of plane-parallel waveguide. It is loaded via the boundary L^- into the same plane-parallel waveguide B.
- A periodic (the length of period is equal to l) chain of storage resonators with the width d and height h coupled with the field of the wave directed by the dielectric waveguide via the beyond cut off coupling windows (their width is equal to d_1) in thin (the thickness is equal to 0.02) diaphragms is located at an aiming distance c from the dielectric waveguide. Energy is accumulated in this chain only when the frequency of the incident wave (operating frequency) coincides with the real part of one of the complex eigen frequencies of the storage resonators. Its period l and the deceleration coefficient $\gamma(k)$ of the surface wave must be matched in such way that at the operating frequency, only one of the spatial harmonics of the periodic structure can propagate without attenuation in its radiation zone [1, 19].
- A dielectric screen (lock or switch, $\varepsilon_{\text{lock}} = 1.0$) with a dynamic parameter $\sigma_{\text{lock}}(t) \geq 0$ locks the resonator chain when the device is operating in the energy storage mode ($0 \leq t \leq t_{\text{accum}} \gg 1$, $\sigma_{\text{lock}}(t) = 5.7 \cdot 10^4$) and quickly (within the interval, $t_{\text{accum}} \leq t \leq t_{\text{rad}}$, $t_{\text{rad}} - t_{\text{accum}} \approx 1.0$) opens the chain when switches to the 'radiation' operating mode ($\sigma_{\text{lock}}(t) = 0$ for $t > t_{\text{rad}}$).

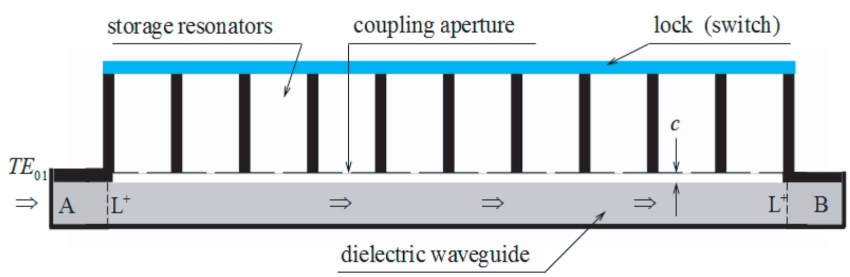

Figure 2: Geometry of an electrodynamic structure implementing the second of proposed schemes. Section by plane $x = \text{const}$.

3. MATHEMATICAL MODELS

The proposed schemes have been analyzed in the framework of the model of the method of exact absorbing conditions, based on the solution to the following initial-boundary value problem [1, 3]:

$$\left\{ \begin{array}{l} \left[-\varepsilon(g)\,\partial_t^2 - \eta_0 P + \partial_y^2 + \partial_z^2\right] U(g,t) = 0; \quad g = \{y,z\} \in \Omega_{\text{int}}, \quad t > 0 \\ U(g,0) = 0, \quad \partial_t U(g,t)|_{t=0} = 0; \quad g \in \overline{\Omega_{\text{int}}} \\ \mathbf{E}_{\text{tg}}(q,t) \text{ and } \mathbf{H}_{\text{tg}}(q,t), \text{ where } q = \{x,y,z\}, \text{ are continuous} \\ \text{when crossing } \Sigma^{\varepsilon,\sigma}, \ \mathbf{E}_{\text{tg}}(q,t)|_{q\in\Sigma} = 0 \text{ and } D^-\left[U(g,t)\right]|_{g\in\text{L}^-} = 0, \\ D^+\left[U(g,t) - V_p(g,t)\right]|_{g\in\text{L}^+} = 0, \quad D\left[U(g,t)\right]|_{g\in\text{L}} = 0; \quad t \geq 0. \end{array} \right. \tag{1}$$

Here, $V_1(g,t) = v_1(z,t)\mu_1(y)$, $g = \{y,z\} \in \text{A}$ is the E_x-component ($E_y = E_z = H_x \equiv 0$) of eigen TE_{01}-wave of plane-parallel waveguide A, incident at times $t > 0$ on the virtual boundary L^+; $U(g,t) = E_x(g,t)$, $P[U] \equiv \partial_t[\sigma(g,t)U(g,t)]$; $\mathbf{E}(q,t) = \{E_x, E_y, E_z\}$ and $\mathbf{H}(q,t) = \{H_x, H_y, H_z\}$ are the electric and magnetic field vectors; $\{x,y,z\}$ are the Cartesian coordinates; the piecewise-constant functions $\sigma(g,t) \geq 0$ and $\varepsilon(g) > 0$ are the specific conductivity and relative permittivity of the object's non-magnetic elements; $\eta_0 = (\mu_0/\varepsilon_0)^{1/2}$ is the impedance of free space; ε_0 and μ_0 are the electric and magnetic vacuum constants. The surfaces $\Sigma = \Sigma_x \times [|x| \leq \infty]$ of perfectly conducting elements of a structure and the surfaces $\Sigma^{\varepsilon,\sigma} = \Sigma_x^{\varepsilon,\sigma} \times [|x| \leq \infty]$ of discontinuities of its material parameters are assumed to be sufficiently smooth. Nonzero components of the electromagnetic field in the plane $y0z$ are determined by the relations

$$\partial_t H_y(g,t) = -\eta_0^{-1}\partial_z E_x(g,t), \quad \partial_t H_z(g,t) = \eta_0^{-1}\partial_y E_x(g,t). \tag{2}$$

The computation domain Ω_{int} in (1) is the part of the plane $y0z$ bounded by the contours Σ_x together with the virtual boundaries $\text{L}^\pm$ (input and output ports in the cross-sections of the virtual waveguides A and B) and virtual spherical boundary L separating the domain Ω_{int} and the free space domain Ω_{ext}. Boundary L is a circle with a radius L centered at the origin of the Cartesian ($\{y, z\}$) and polar ($\{\rho, \phi\}$) coordinates. It covers all scattering inhomogeneities of the domain Ω_{int}.

Exact absorbing conditions $D^+[U(g,t)-V_1(g,t)]|_{g\in \text{L}^+} = 0$, $D^-[U(g,t)]|_{g\in \text{L}^-} = 0$, and $D[U(g,t)]|_{g\in \text{L}} = 0$ for the virtual boundaries provide an ideal model for the outgoing from Ω_{int} into domains A, B and Ω_{ext} waves

$$\begin{aligned} U(g,t) - V_1(g,t) = U^+(g,t) = \sum_{n=1}^{\infty} U_n^+(g,t) = \sum_{n=1}^{\infty} u_n^+(z,t)\,\mu_n(y); \quad g \in \bar{\text{A}}, \quad t \geq 0, \\ U(g,t) = U^-(g,t) = \sum_{n=1}^{\infty} U_n^-(g,t) = \sum_{n=1}^{\infty} u_n^-(z,t)\,\mu_n(y); \quad g \in \bar{\text{B}}, \quad t \geq 0, \text{ and} \\ U(g,t) = \sum_{m=-\infty}^{\infty} u_m(\rho,t)\bar{\mu}_m(\phi); \quad \rho \geq L, \quad 0 \leq \phi \leq 2\pi, \quad t \geq 0. \end{aligned} \tag{3}$$

This means that they do not distort the physics of the processes simulated by mathematical means when the problem's computation space is limited by the domain Ω_{int}.

Operators $D^+[\ldots]$, $D[\ldots]$ and orthonormal systems of transverse functions $\{\mu_n(y)\}_{n=1}^{\infty}$, $\{\bar{\mu}_m(\phi)\}_{m=-\infty}^{\infty}$ complete on the corresponding intervals are defined in [1,3]. The transition to the amplitude-frequency characteristics, after solving problem (1) using standard computational schemes of the finite difference method [14] and determining the function $U(g,t)$ on $g \in \overline{\Omega_{\text{int}}} \cup \Omega_{\text{ext}}$ and at time moments $t \in [0,T]$, $T < \infty$ is carried out using the integral transformation $\tilde{f}(k) = \int_0^T f(t)\exp(ikt)dt$ ($\tilde{f}(k) \leftrightarrow f(t)$), $k = 2\pi/\lambda$ — is a wave number, λ — is a wavelength in the free space. As a result, practically all quantities characterizing these processes in one way or another are available for the analysis of the physics of processes. Below only those that we used when processing the results of computational experiments are listed.

- Functions $U(g,t) = E_x(g,t)$, $0 \leq t \leq T$ at any fixed point g of computational domain Ω_{int} as well as the spatial distribution of values $E_x(g,t)$, $g \in \overline{\Omega_{\text{int}}}$ at any fixed point in time $t \in [0,T]$.
- $W_{\text{inc, L}^+}(t_2;t_1)$, $W_{\text{rad, L}^+}(t_2;t_1)$, $W_{\text{rad, L}^-}(t_2;t_1)$ and $W_{\text{rad, L}}(t_2;t_1)$, those are the energy supplied to a structure through a virtual boundary L^+, taken away through this boundary into the waveguide A, taken away across the boundary L^- into the waveguide B, and radiated into free space Ω_{ext} via a virtual boundary L (all for a time interval $t_1 \leq t \leq t_2$).
- $D(\phi,k,M) = \frac{|\tilde{E}_x(M,\phi,k)|^2}{\max\limits_{\Phi_1\leq\phi\leq\Phi_2} |\tilde{E}_x(M,\phi,k)|^2}$, $0 \leq \Phi_1 \leq \phi \leq \Phi_2 \leq 360°$, $K_1 \leq k \leq K_2$, that is the normalized radiation pattern calculated along the arc $\rho = M \geq L$.
- $\phi = \bar{\phi}(k)$, that is an angle determining the orientation of the main lobe: $D(\bar{\phi}(k),k,M) = 1.0$.
- $\phi_{0.5}(k)$, that is the half-power beam width: $\phi_{0.5}(k) = \phi^+ - \phi^-$, $\bar{\phi} \in [\phi^-, \phi^+]$, where $D(\phi^+,k,M) = 0.5$ and $D(\phi^-,k,M) = 0.5$.

The values of $W_{\text{inc, L}^+}(t_2;t_1)$, $W_{\text{rad, L}^\pm}(t_2;t_1)$ and $W_{\text{rad, L}}(t_2;t_1)$ are determined by integration over t in the interval $t_1 \leq t \leq t_2$ of values of instantaneous powers, 'transferred' through the corresponding boundaries (see, for example, works [1,3]).

4. SOME NUMERICAL RESULTS

Below we briefly illustrate only one of the results of the extensive numerical simulation. Putting $\varepsilon = 2.5$, $\sigma = 0$, $a = 1.02$, $\bar{l} = 16.0$, $c = 0.04$, $\sigma_{\text{lock}}(t) = 5.7 \cdot 10^4$, the height (from the dielectric waveguide) and the thickness of the main mirrors equal to 4.0 and 0.1, respectively, and the aperture window width equal to 0.22, in the geometry of the structure shown in Fig. 1, let us excite it with a pulsed TE_{01}-wave occupying the frequency band $2.2 \leq k \leq 3.8$. In this frequency range, only the TE_{01}-wave $\tilde{U}_1^+(g,k) \leftrightarrow U_1^+(g,t)$ propagates in the waveguide without attenuation, while the window of the diaphragm connecting the waveguide and the resonant volume remains beyond the cutoff. The resonant volume during the observation time $0 \leq t \leq T$ is isolated from the grating by an impenetrable screen.

Having calculated the values of the function $U(g,t)$, $0 < t \leq T = 2000$ at several points g lying on the axis of the dielectric waveguide, we determine [3.33–35] from the spikes on the curves $\tilde{U}(g,k) \leftrightarrow U(g,t)\chi(t-\bar{T})\chi(T-t)$ ($\bar{T} = 100$ — the duration of initial pulse, $\chi(\ldots)$ is the

Heaviside step function), the real parts $\mathrm{Re}\bar{k}$ of complex valued eigen frequencies $\bar{k} = \mathrm{Re}\bar{k} + i\mathrm{Im}\bar{k}$ ($\mathrm{Im}\bar{k} < 0$) of free H_{01m}-field's oscillations, excited by a pulse signal in the resonant volume. These oscillations are composed by counterpropagating surface waves of the dielectric waveguide. Let us choose one of these eigen frequencies ($\bar{k}$: $\mathrm{Re}\bar{k} = 3.699$) and excite the structure with a sufficiently long ($\bar{T} = 2000$) quasi-monochromatic pulse with a central frequency $\tilde{k} = \mathrm{Re}\bar{k}$. The results of this computational experiment allow us [3, 33–35] to determine the configuration of the oscillation's field corresponding to the selected resonant frequency (see Fig. 3 — this is $H_{0,1,27}$-oscillation, the length $\lambda_{\mathrm{wave}} \approx \bar{l}/13.5$ of the surface waves, composing it, is approximately equal to 1.19), and to calculate the values $\mathrm{Im}\bar{k} = -0.000248$ and the quality factor of the oscillation $Q = \mathrm{Re}\bar{k}/2|\mathrm{Im}\bar{k}| \approx 7460$. Amplitudes $U(g, t)$ in the antinodes of the field of this oscillation on the interval $0 < t \leq \bar{T}$ grow fast enough so that this oscillation can be used as an operating one in the model of the device considered here, designed for the formation and directional emission of powerful short radio pulses.

Wavelength λ_{wave} of surface waves of a planar waveguide at a frequency $k = \mathrm{Re}\bar{k} = 3.699$ defines the period of grating $l = 1.19$, having basic and only propagating spatial harmonic, that, when the substrate transforms into a layer completely transparent for electromagnetic waves (this will happen at the time $t_{\mathrm{rad}} = t_{\mathrm{accum}} + 1$), will be directed along the axis y. Let it be lamellar grating, with width $d = 1.0$ and depth $h = 1.25$ (see Fig. 1). Such a grating provides at frequency $k = \mathrm{Re}\bar{k} = 3.699$ a sufficiently effective transformation of a monochromatic surface wave of a planar waveguide into its own propagating spatial harmonic [27–30].

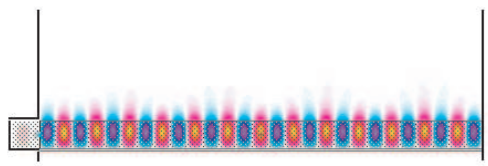

Figure 3: The field configuration of the working oscillation device layout.

We now excite a structure with a grating by a very long quasi-monochromatic pulse ($\tilde{k} = \mathrm{Re}\bar{k} = 3.699$) such that on the interval $t \leq \bar{T} = t_{\mathrm{accum}} = 6000$ it would be possible to observe the process of energy accumulation in the field of the working oscillation, and then, at $t > t_{\mathrm{rad}} = t_{\mathrm{accum}} + 1 = 6001$, — the process of radiation of this energy into free space ($\sigma_{\mathrm{lock}}(t) = 0$ for $t > t_{\mathrm{rad}}$). The results of the computational experiment are presented in Figs. 4 and 5.

The principal characteristic of the storage mode — the accumulation efficiency at each specific point in time t ($\eta_{\mathrm{accum}}(t) = W_{\mathrm{accum}}(t; 0)/W_{\mathrm{inc,\,L^+}}(t; 0)$, $W_{\mathrm{accum}}(t; 0) = W_{\mathrm{inc,\,L^+}}(t; 0) - W_{\mathrm{rad,\,L^+}}(t; 0) - W_{\mathrm{rad,\,L}}(t; 0)$) — is presented at the right fragment of Fig. 4. It defines a moment in time $t = t_{\max}$ ($t_{\max}$: $\eta_{\mathrm{accum}}(t_{\max}) = \max\limits_{0<t<t_{\mathrm{accum}}} \eta_{\mathrm{accum}}(t)$), when the efficiency of the device reaches its highest value. At this time moment, it is necessary to switch from the energy storage mode to the radiation mode. In the case under consideration $t_{\max} \approx 5000$ $\eta_{\mathrm{accum}}(t_{\max}) \approx 0.71$.

In the time interval $t_{\mathrm{accum}} = 6000 \leq t \leq 6001 = t_{\mathrm{rad}}$, the structure switches from the mode of energy storage to the mode of its radiation. The planar waveguide substrate, which is opaque for electromagnetic waves, 'disappears', surface waves composing the operating oscillation 'sweep' the grat-

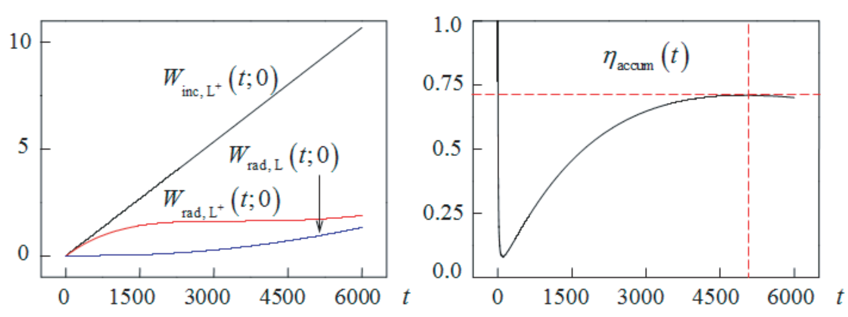

Figure 4: Distribution of the supplied energy when the structure is operating in the storage mode and the storage efficiency as a function of time.

ing, generating the so-called diffraction radiation at its fundamental spatial harmonic. The dependences $U(g,t)$, $t > t_{\rm rad}$, taken at points $g = g_1 \div g_3$ (see the left fragment of Fig. 5) and the behavior of the function $W_{\rm rad,\ L}(t;0)$ after switching of the structure to the radiation mode allow us to estimate the effective duration $\Delta t_{\rm effect}$ of the radiated pulse (it is approximately equal to 46) and the degree of compression (compression ratio) $\beta = t_{\rm accum}/\Delta t_{\rm effect} \approx 130$. The ratio of the energies 'stored' in the emitted pulse ($W_{\rm rad,\ L}(6060; t_{\rm rad}) \approx 7.4$) and in the input pulse ($W_{\rm inc,\ L^+}(t_{\rm accum}; 0) \approx 10.7$) determines the radiation efficiency of the device $\eta_{\rm rad} = W_{\rm rad,\ L}(3050; t_{\rm rad})/W_{\rm inc,\ L^+}(t_{\rm accum}; 0) \approx 0.69$ and its power amplification factor $\zeta = \beta \cdot \eta_{\rm rad} \approx 89.7$. The radiation directivity is close to the expected one (see the right fragment of Fig. 5), the width of the main lobe of the radiation pattern is small and equal, approximately, to 6°. More accurate selection of all system parameters can significantly improve these rather good characteristics.

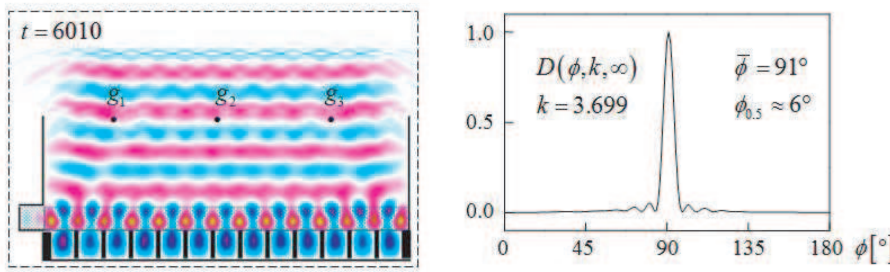

Figure 5: Patterns of $E_x(g,t)$, $g \in \Omega_{\rm int}$ at the time instant $t = 6010$ and the radiation pattern of the emitter at the operating frequency $k = 3.699$.

5. CONCLUSION

The results obtained in extensive numerical experiments allow us to assert that the proposed rather simple schemes for the formation and directional radiation of high-power short radio pulses are quite efficient and can be implemented when creating innovative energy compressing devices in the microwave range.

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