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DESIGN AND SIMULATION OF HIGH-POWER PLANAR ČERENKOV OSCILLATORS WITH TWO-DIMENSIONAL DISTRIBUTED FEEDBACK IN THE SUBTERAHERTZ FREQUENCY RANGE

N. Yu. Peskov,[1,2*] **V. Yu. Zaslavsky,**[1,2]
N. S. Ginzburg,[1,2] **A. M. Malkin,**[1] **A. A. Savilova,**[1]
A. S. Sergeev,[1] **A. V. Arzhannikov,**[2] **P. V. Kalinin,**[2]
E. S. Sandalov,[2] **S. L. Sinitsky,**[2], **and V. D. Stepanov**[2] UDC 621.385

We study the possibility to advance relativistic planar Čerenkov surface-wave oscillators, which are driven by intense sheet electron beams, to the subterahertz frequency range within the framework of the performed simulation. It is shown that the use of two-dimensional periodic slow-wave structures providing the two-dimensional distributed feedback allows one to ensure high coherence of radiation at the subgigawatt power level in oscillators of this kind for transverse sizes equal to hundreds of wavelengths. The design parameters and structural elements are discussed for implementing such high-power oscillators based on the ELMI accelerator complex within the framework of the joint BINP/IAP experiments.

1. INTRODUCTION

Since the first successful realizations in the experiments performed already in the 1970s [1, 2], relativistic oscillators based on the Čerenkov mechanism of induced radiation of high-current electron beams have remained the highest-power sources of pulsed radiation in the centimeter-wave range and the long-wavelength part of the millimeter-wave range [3–8]. However, increasing the power generated by them and shortening the wavelength of their radiation are inevitably accompanied by the issue of the oversize increase of their interaction space. Therefore, one of the most topical tasks in developing such oscillators in the short-wavelength ranges is to ensure selection of modes with respect to their transverse indices.

A few methods are known, which have been developed to solve this problem in the Čerenkov devices, including cyclotron selection of parasitic modes [9, 10], partitioning of the interaction space [11–14], etc. They allow one to discriminate excitation of parasitic modes with the transverse sizes (diameters) of the system being equal to several (up to 2–3) radiation wavelengths λ.

In the 1990s, the multigigawatt power level of microwave pulses in the centimeter-wave range was reached mainly due to the development of the so-called multi-wave Čerenkov oscillators operated at system diameters of about $(4–5)\lambda$ [6, 7]. However, simulation by the particle-in-cell (PIC) method shows that the generation regimes in such devices are multistable even for existing oversize parameters and, therefore, changes in the field structure and radiation frequency can be observed as the beam parameters vary both

* peskov@ipfran.ru

[1] A. V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia; [2] G. I. Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 66, Nos. 7–8, pp. 566–574, July–August 2023. Russian DOI: 10.52452/00213462_2023_66_07_566 Original article submitted June 14, 2023; accepted July 19, 2023.

during one pulse and from pulse to pulse [15]. According to simulations, the further oversize increase leads to the loss of the radiation coherence.

A radical way to solve the problem of mode selection in high-power oversized relativistic masers is to use two-dimensional distributed feedback [16]. The latter involves ensuring the spatial coherence of radiation by using highly selective electrodynamic systems, namely, two-dimensional (2D-periodic) Bragg structures. The theoretical and experimental studies, which have been performed so far, have demonstrated the high potentialities of using two-dimensional distributed feedback for generation of high-power narrow-band radiation in various relativistic masers, whose transverse sizes exceed the wavelength by an order of magnitude or more [17]. Operability of the new feedback mechanism was demonstrated in free-electron masers (FEMs) with transverse system sizes of up to 50λ and output power levels of 50–100 MW in the Ka [18] and W [19, 20] bands. The oversize parameter, which has been achieved in these experiments, is comparable with that of the megawatt gyrotrons developed for up-to-date fusion facilities [21, 22].

A promising line of advancing the concept of two-dimensional distributed feedback is the development of relativistic oscillators based on the Čerenkov mechanism of electron-wave interaction [23–25]. In contrast to FEMs, oscillators of this type use the radiation of relativistic electron beams moving rectilinearly, which makes the system of beam formation and transportation much simpler and significantly reduces the requirements imposed on the spread in the beam parameters. As a result, the Čerenkov interaction mechanism affords the use of more intense electron beams compared with the FEMs and, therefore, a further increase in the output radiation power. The mechanism of two-dimensional distributed feedback in Čerenkov-type oscillators is realized by using two-dimensionally periodic slow-wave structures. In this case, such structures combine the properties of a slow-wave system, which ensures high-efficiency interaction with a wide high-current rectilinear relativistic electron beam, and a high-Q cavity where (similar to the FEMs) the radiation is synchronized with respect to the "wide" transverse coordinate due to the formation of transverse wave beams. At the same time, the slow surface waves, which are formed over two-dimensionally periodic slow-wave structures, specify the field structure along the perpendicular to the plane of the slow-wave structure, thus ensuring the specified spatial structure along this coordinate for an arbitrarily oversized waveguide.

Creation of superpower planar oscillators of the Čerenkov type is initiated currently in the joint effort of the G. I. Budker Institute of Nuclear Physics (BINP) of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk) and the Institute of Applied Physics (IAP) of the Russian Academy of Sciences (Nizhny Novgorod) on the basis of the ELMI high-current accelerator complex. The experiments are proposed to start in the W band (an operating frequency of 75 GHz) with the system transverse size about 50 wavelengths [26]. In this work, we study the prospects of advancing the developed oscillators to the subterahertz frequency range, while retaining the transverse sizes of the beam. Their spatiotemporal dynamics is simulated within the framework of the developed quasioptical model of the electron-wave interaction [24, 27] and the three-dimensional PIC code of the CST Studio Suite. We have estimated the parameters for realization of oscillators that are based on the ELMI accelerator and operated in the G and J bands (at frequencies of 150 GHz and 300 GHz, respectively), which have record-breaking transverse sizes of up to 100λ and 200λ, respectively, and ensure the subgigawatt level of the output radiation power.

2. OPERATION PRINCIPLE AND CALCULATION PARAMETERS

The diagram of the electrodynamic system of a planar Čerenkov surface-wave oscillator with two-dimensional distributed feedback is shown in Fig. 1. The main element of the oscillator is the two-dimensionally periodic slow-wave structure

$$a = \frac{a_1}{2}\cos(\bar{h}x)\cos(\bar{h}z), \tag{1}$$

where $\bar{h} = 2\pi/d$, d is the corrugation period along the x and z coordinates, and a_1 is the corrugation depth. The so-called π-type regime is chosen for the operation of the oscillator, where the slowing-down of the fundamental harmonic of the field takes place, which increases significantly the impedance of coupling with the electron beam. Oscillators of this type are conventionally called the surface-wave oscillators. The above-mentioned multi-wave Čerenkov oscillators also operate in this regime. Within the framework of the quasioptical model, the radiated field can be represented as four partial wave beams:

$$\mathbf{E} = \mathbf{E}_A^0[A_+ \exp(-ihz) + A_- \exp(ihz)] \exp(i\omega t) + \mathbf{E}_B^0[B_+ \exp(-ihx) + B_- \exp(ihx)] \exp(i\omega t), \qquad (2)$$

where $A_+(x, y, z, t)$, $A_-(x, y, z, t)$, $B_+(x, y, z, t)$, and $B_-(x, y, z, t)$ are slow functions of the coordinates and the time, and $\mathbf{E}_A^0$ and $\mathbf{E}_B^0$ are structural factors that characterize the polarization of the corresponding waves. Two of the above wave beams, A_+ and A_-, are co- and counterpropagating with respect to the translational electron velocity ($\pm z$), and the other two, B_+ and B_-, propagate in the transverse directions ($\pm x$), synchronizing the radiation of a wide sheet relativistic electron beam. Wave beams (2) are coupled on the two-dimensionally periodic Bragg structure (1) under the Bragg resonance conditions

$$h \approx \bar{h} \qquad (3)$$

and form the operating surface wave.

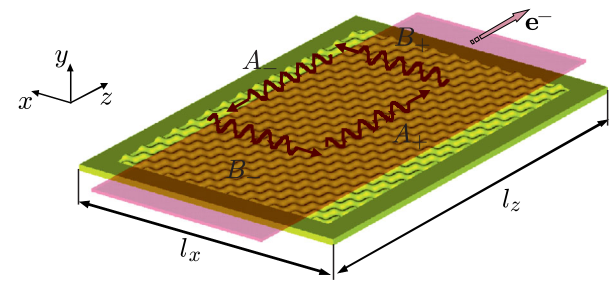

Fig. 1. Scheme of the interaction space of a planar surface-wave oscillator with a two-dimensionally periodic slow-wave structure ensuring the mechanism of the two-dimensional distributed feedback. The sheet relativistic electron beam e^-, which moves over the structure, is shown along with the propagation directions of partial wave beams forming the feedback circuit.

Currently, experiments on implementation of high-power short-wavelength Čerenkov oscillators are performed jointly by BINP and IAP [26] on the basis of the ELMI accelerator complex (1 MeV/10 kA/3 μs) at BINP, which allows one to form ribbon electron beams having a transverse size (width) of about 18 cm and a width of 2–3 mm. The beams are focused by a guiding magnetic field of about 1.2 T and transported in a vacuum channel with the cross section 0.9×20 cm.

Planar surface-wave oscillators were simulated in the G and J bands at frequencies of about 150 GHz and 300 GHz, respectively. Based on the results of the optimization performed in the simulation, slow-wave systems were designed for operation in these bands. The corrugation used in the G band (a frequency of about 150 GHz) had the two-dimensionally periodic sine-shaped profile with the depth $a_1 \approx 0.8$ mm and the period $d \approx 1.7$ mm with respect to the x and z coordinates. The length of the structure was $l_z \approx 12$–15 cm. The slow-wave structure for operation in the J band (a frequency of 300 GHz) had the following parameters: $a_1 \approx 0.4$ mm, $d_{x,z} \approx 0.85$ mm, and $l_z \approx 10$ cm. The maximum width of the relativistic electron beam formed by the ELMI accelerator was assumed to be used in both bands, and the width of the structures was $l_x \approx 20$ cm, which corresponded to the transverse oversize parameters $l_x/\lambda \sim 100$ and $l_x/\lambda \sim 200$ in the G and J bands, respectively. The corrugation was specified on one of the plates of the planar waveguide, and the transportation of the relativistic electron beam was designed to occur at a distance of about 0.5 mm from the slow-wave structure in order to ensure the effective electron-wave interaction.

3. SIMULATION RESULTS

The parameters for implementation of planar surface-wave oscillators on the ELMI accelerator were estimated on the basis of the developed self-consistent spatiotemporal model of the electron-wave interaction (for more detail, see [24, 27]). Within the framework of this model, evolution of the wave beams (2), which form the surface wave over the two-dimensionally periodic corrugation (1), is described by the equations of coupled waves in the quasioptical approximation with allowance for excitation of the synchronous wave by the electron beam, and the amplitude of the high-frequency electron current is determined from the averaged electron motion equations. The electronic efficiency is found using these equations as a result of averaging the particle energy with respect to the initial entry phases (the so-called large-particle method). The geometry of the slow-wave system (see Sec. 2), the transverse size and parameters (initial energy, current per unit length, velocity spread, etc.) of the sheet relativistic electron beam, and the parameters characterizing the electron-

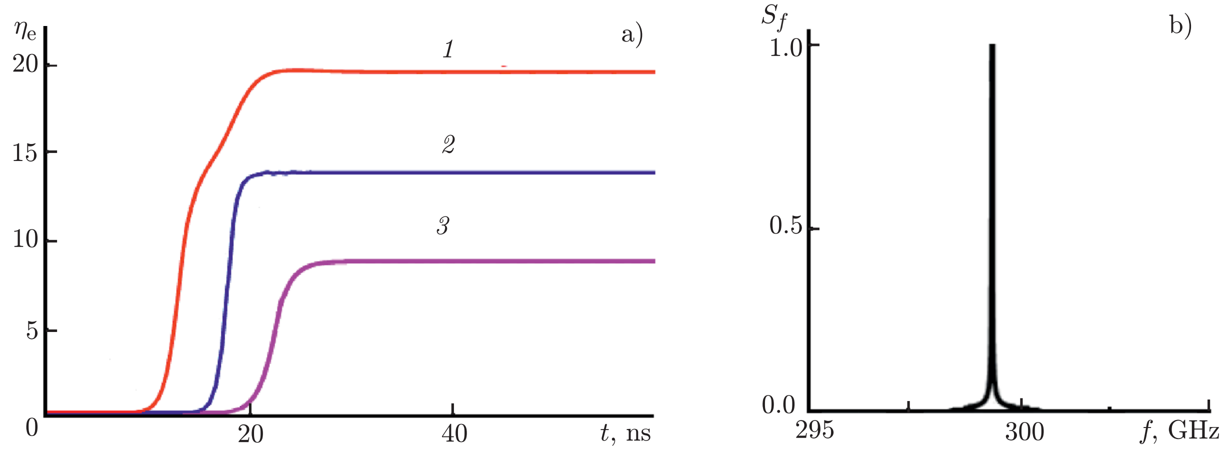

Fig. 2. Results of simulation of surface-wave oscillators with two-dimensional distributed feedback on the basis of the ELMI accelerator in various frequency bands (quasioptical model). Time dependence of the electron efficiency η_e for a frequency of 75 GHz (curve *1*), 150 GHz (curve *2*), and 300 GHz (curve *3*) (*a*). The radiation spectrum in the stationary regime in the J-band oscillator (*b*).

wave interaction in the oscillator (amplification parameter, parameter of the inertial electron bunching, etc.) corresponded to the conditions of the planned ELMI accelerator experiments.

The results of simulating surface-wave oscillators with two-dimensional distributed feedback within the framework of the developed quasioptical model are presented in Figs. 2 and 3. The simulation demonstrates the setting of the stationary generation regime at the design parameters of the structures and the optimal parameters of the relativistic electron beam in both bands under consideration. For comparison, Fig. 2*a* shows the results of simulating the W-band Čerenkov surface-wave oscillator with an operating frequency of about 75 GHz, which is currently studied experimentally using the ELMI accelerator [26]. The simulation shows that advancing the oscillators to the short-wavelength ranges is accompanied by an increase in the time of the self-oscillation setting and an inevitable decrease in the electronic efficiency. As a result, the calculated electron efficiency is equal to 12–15% in the G band, and 7–9% in the J band, whereas at a total beam current of about 3.0–3.5 kA (the current per unit length is 170–200 A/cm), the radiation power can reach 0.4–0.5 GW and 0.2–0.3 GW in the above-mentioned bands, respectively. The ohmic loss in these bands does not exceed 25–30% of the output power. The characteristic time of the oscillation setting is about 20–25 ns.

It should be noted that in order to achieve a relatively high efficiency of the electron-wave interaction in Čerenkov oscillators, it is proposed to reduce the thickness of the sheet relativistic electron beam to 1.0–1.5 mm. Under the conditions of the initial ELMI accelerator experiments, this can be done by cutting out the central part of the beam with the minimum spread in parameters (with the corresponding decrease in the total current of the beam to the above-specified value). The simulation shows that the intensity of the electron-wave interaction decreases sufficiently fast, when the distance from the slow-wave structure, where the beam is transported, increases.

The structure of the partial waves excited by the electron beam in the J-band oscillator in the stationary regime is presented in Fig. 3. At optimal parameters, there occurs excitation of the fundamental mode of the two-dimensionally periodic structure with one oscillation of the field over the longitudinal coordinate z and the "wide" transverse coordinate x (see Figs. 3*a* and 3*b*). The profile of the field of the operating wave with respect to the "narrow" transverse coordinate y directed along the gap of the planar waveguide demonstrates formation of a slowed-down surface wave, which is tightly bound to the two-dimensionally periodic structure (Figs. 3*c* and 3*d*).

To verify the averaged theoretical models, we compared the above-presented results with the results of the total three-dimensional simulation using the PIC code in the CST Studio Suite. The simulation was

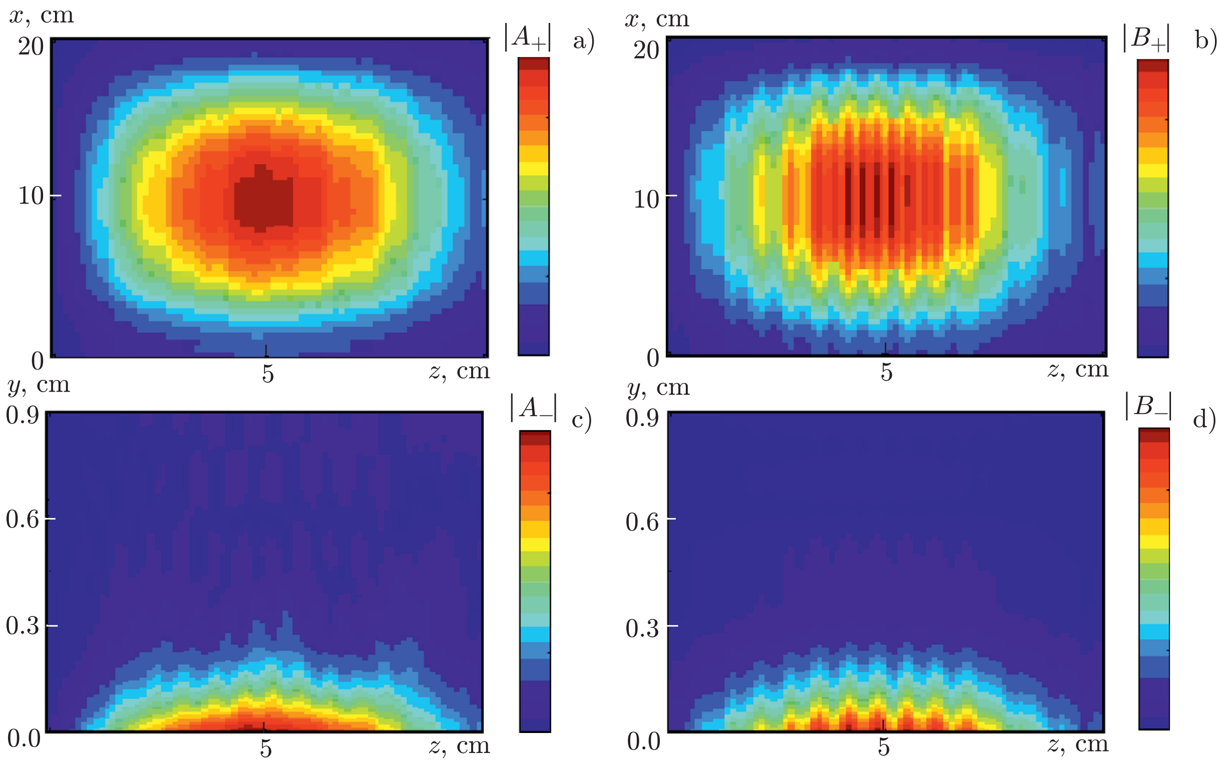

Fig. 3. Structures of the fields of partial waves in the stationary regime in a planar Čerenkov J-band surface-wave oscillator with the two-dimensional distributed feedback (quasioptical model and an operating frequency of about 300 GHz). The values of $|A_+|$ and $|B_+|$ increase from the blue color to the red one.

performed both for the perfect beam and with allowance for the velocity spread, whose value corresponded to the electron optical measurements and the results of three-dimensional simulation of the beam dynamics of the ELMI accelerator, which was described in [26]. The comparison shows good agreement of the results obtained in the three-dimensional simulation and within the framework of the quasioptical approach. The PIC simulation of the J-band surface-wave oscillator confirms the possibility of its implementation at the optimal parameters of the narrow-band generation regime (Fig. 4). The electron efficiency achieved as a result of optimization (with allowance for the velocity spread of the beam and the conditions of its transportation in the interaction space) was about 7%.

The longitudinal and transverse structures of the RF field in the thee-dimensional simulation also demonstrate the formation of an operating surface wave. In the steady-state regime, it is close to the structure of the fundamental mode obtained within the framework of the quasioptical theory (see Figs. 3 and 4). In the developed planar oscillator scheme, the two-dimensionally periodic slow-wave structure ensures the coupling of longitudinally propagating wave beams of the TM type (waves A_+ and A_-) and transversely propagating wave beams of the TE type (waves B_+ and B_-). This allows separating these wave beams with respect to their polarization in the spatial distribution of the RF field: the component H_x of the mangetic field corresponds to the superposition of the wave beams A_+ and A_-, which ensure the interaction with the sheet relativistic electron beam, and H_z corresponds to the superposition of the synchronization waves B_+ and B_- (see Fig. 4c–4f).

As it has already been noted, a specific feature of the Čerenkov surface-wave oscillator with the two-dimensional distributed feedback is the presence of four wave beams propagating in the $\pm z$ and $\pm x$ directions. According to the simulation performed, at the optimal parameters the main part of the energy radiated by the electron beam in the developed oscillators is concentrated in the partial wave beams that are copropagating (A_+) and counterpropagating (A_-) with respect to the motion of the relativistic electron beams. The power ratio in these wave beams can vary depending on the detuning of the synchronism of the

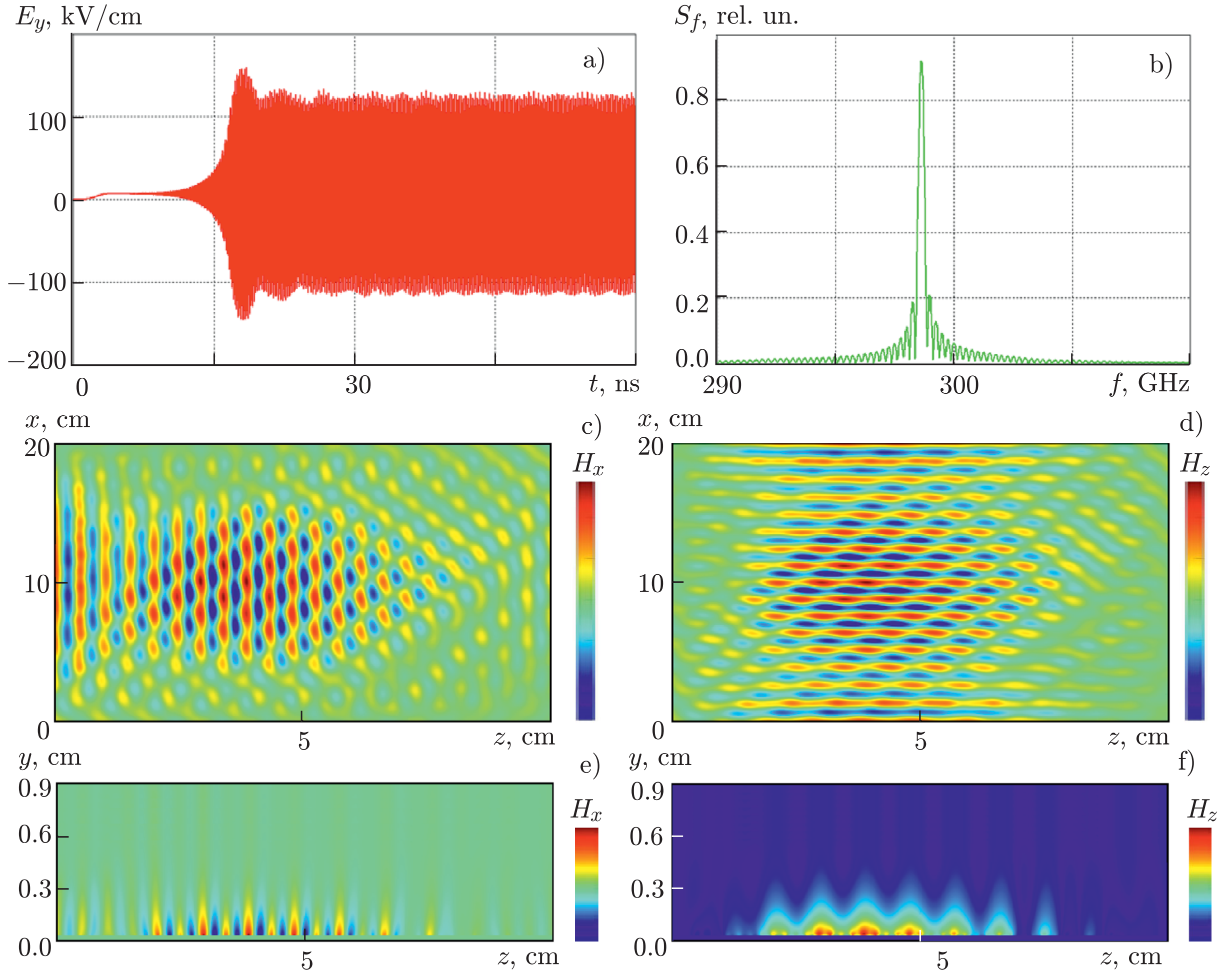

Fig. 4. Results of three-dimensional simulation of the surface-wave oscillator with two-dimensional distributed feedback in the band near 300 GHz on the basis of the ELMI accelerator (the CST Studio Suite code): setting of the narrow-band generation regime at optimal parameters. Time dependence of the amplitude of the field E_y at the oscillator output (*a*), the radiation spectrum (*b*), and the structure of the RF field in the stationary regime in the xz plane (*c* and *d*) and the yz plane (*e* and *f*). The magnetic-field component H_x (*c* and *e*) corresponds to the superposition of the longitudinally propagating wave beams A_+ and A_-, and the component H_z (*d* and *f*) corresponds to the superposition of the transversely propagating synchronization waves B_+ and B_-. The values of $|H_x|$ and $|H_z|$ increase from the blue color to the red color.

electron-wave interaction. To ensure the unidirectional output of the radiation toward the collector, we are planning to install additional Bragg reflectors, which reflect the counterpropagating wave beam A_-, on the cathode side of the oscillator [26]. Such additional reflectors allow ensuring almost complete conversion of this wave beams to the copropagation direction and, as the simulation shows, does not reduce the efficiency of the electron-wave interaction if the phase (i.e., the distance between the reflector and the slow-wave structure) is chosen appropriately. According to the simulation, the radiation power is relatively low in the transverse synchronization waves B_+ and B_-. Under the conditions of the demonstration experiments, these transverse wave beams are assumed to be scattered by absorbers or scatterers with irregular (random) surface profiles, which will be installed on the side ends of the vacuum channel. A similar scheme was used on the ELMI accelerator in the earlier experimental implementations of FEM oscillators with two-dimensional distributed feedback [19, 20].

It should be emphasized that for the sake of comparison, the conventional scheme of surface-wave oscillators with one-dimensionally periodic slow-wave structures was simulated in the above-mentioned bands. The simulation showed that excitation of a great number of modes with different transverse (with respect to the x coordinate) indices was observed in such schemes already at the width $l_x \sim (10\text{–}20)\lambda$, which resulted in loss of coherence of the radiation. At the same time, when using two-dimensionally periodic structures, the simulation demonstrates the setting of a stable narrow-band generation regime with a controllable spatial structure of the radiated field up to the maximum width $l_{\text{beam}} \sim 18$ cm of the sheet beam, which can be achieved on the ELMI accelerator (in the bands under consideration, it corresponds to the oversize parameter $l_x/\lambda \sim 100\text{–}200$).

4. DISCUSSION AND CONCLUSIONS

Thus, the performed theoretical analysis and computer simulation have demonstrated the prospects of using two-dimensionally periodic structures, which are based on the mechanism of two-dimensional distributed feedback, to produce high-power coherent radiation in planar Čerenkov surface-wave oscillators with high-intensity sheet electron beams. According to the studies performed, such devices can ensure a stable narrow-band generation regime at the transverse sizes amounting to 10^2 wavelengths and more, which opens up the possibility of reaching the subgigawatt pulse power level in the subterahertz frequency range. The possibility to implement such high-power sources, which will eventually outmatch the world analogs [8] , is currently studied in the joint experiments performed by BINP and IAP on the basis of the ELMI high-current accelerator complex.

It should be noted that an effort to create Čerenkov oscillators with two-dimensional distributed feedback in short-wavelength ranges is also made at the University of Strathclyde (UK) now [28, 29], although at a significantly lower oversize level and, as a result, a lower output power.

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