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The use of advanced Bragg reflectors for frequency stabilization and tuning in planar surface-wave oscillators

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To achieve high coherence of radiation in oversized Cherenkov surface-wave oscillators (SWO), the use of an additional resonant Bragg reflector of an advanced type based on the coupling of paraxial and quasi-cutoff waves is proposed. Within the framework of the conducted 3D PIC - simulations, it is shown that the reflectors of this type make it possible to provide a stable narrow-band generation regime in SWO of a planar geometry with excitation of the fundamental mode of the slow-wave structure at an oversize parameter (width) of about 7−10 radiation wavelengths. An additional advantage of the proposed planar generator is the possibility of mechanical frequency tuning when changing the gap size of the resonant reflector. The parameters for the implementation of powerful W-band SWO based on the high-current accelerator complex „ELMI"(BINP RAS) have been evaluated.

Keywords: relativistic Cherenkov generators, high-power microwave radiation, Bragg resonators, mode selection.

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From the first successful implementations [1,2] to the present day [3–8], much attention has been paid to the design of relativistic surface-wave oscillators (SWOs) based on the Cherenkov interaction mechanism. These devices utilize the resonant interaction of a rectilinear relativistic electron beam (REB) with a slow fundamental harmonic of a radio-frequency (RF) field in a periodically corrugated waveguide (slow-wave structure; the so-called π regime), which ensures high impedance of electron-wave coupling. This allows one to increase the oversize parameter and, ultimately, the output power of these oscillators in comparison with similar parameters of other types of Cherenkov devices (backward- and traveling-wave oscillators) with their transverse dimensions limited to 2−3 radiation wavelengths λ. A record-high multi-gigawatt level of radiation power has been achieved in the so-called multiwave Cherenkov generators (an SWO modification that also utilizes near-π interaction) in frequency ranges from X to Ka with an oversize parameter (diameter) of the interaction space of $D/\lambda \geqslant 5$ [3,4].

A surface wave may be regarded as a „supermode," a set of several waveguide modes with correlated phases nestled against the slow-wave structure surface. This solves the problem of spatial coherence of radiation in the direction normal to the surface (in cylindrical geometry, radial) at arbitrary transverse dimensions of the structure. However, the problem of radiation synchronization along the „wide" transverse (azimuthal) coordinate arises at significantly large oversize parameter values. It follows from simulated data (see [9] for details) that even with transverse dimensions $D/\lambda \sim 5$, „canonical" SWO designs based on one-dimensionally (1D) periodic slow-wave structures do, in contrast to SWOs with two-dimensionally (2D) periodic structures [10], lose radiation coherence in transverse (azimuthal) mode indices.

In the present study, the use of an additional advanced resonant Bragg reflector [11,12] at the oscillator input is proposed as a means to ensure radiation coherence in an SWO with a 1D slow-wave structure. The aim of the study is to investigate the feasibility of selective excitation of the fundamental mode in the indicated SWO design with a significant oversize parameter.

The examined SWIO design with a planar geometry is shown in Fig. 1. Its electrodynamic system is based on a 1D slow-wave structure with corrugation

$$a = a_{1D}\cos(h_{1D}z) \quad (1)$$

($h_{1D} = 2\pi/d_{1D}$, d_{1D} is the corrugation period, and a_{1D} is the corrugation amplitude). Within the quasi-optical approach developed in [9], the emitted field may be represented as two counter-propagating quasi-optical wave fluxes

$$\mathbf{E} = \mathbf{E}_A \mathrm{Re}\left[(A_+ e^{-ihz} + A_- e^{ihz})e^{i\omega t}\right] \quad (2)$$

($A_\pm$ are slow amplitudes and $\mathbf{E}_A$ is the structural factor characterizing wave polarization) coupled at this corrugation under Bragg resonance conditions

$$h_{1D} \approx 2h \quad (3)$$

and forming an operating surface wave.

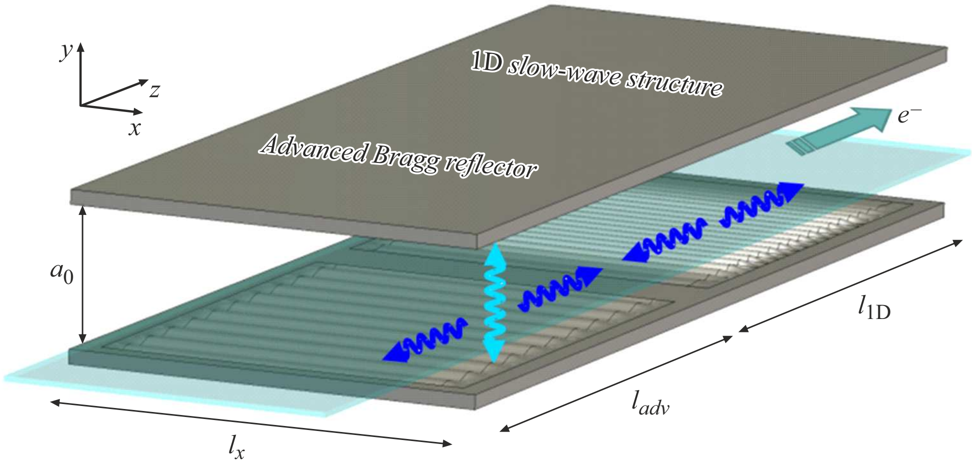

Figure 1. Schematic diagram of a planar Cherenkov surface-wave oscillator with a one-dimensionally periodic slow-wave structure and an advanced input resonant Bragg reflector. The direction of propagation of a sheet electron beam driving the oscillator is indicated. Arrows denote the directions of propagation of partial wave fluxes in different sections of its electrodynamic system.

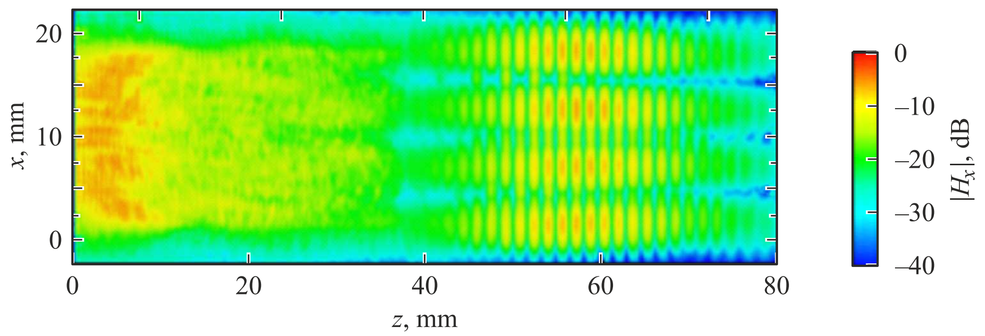

Figure 2. Results of 3D modeling of a W-band surface-wave oscillator with an input broadband (non-resonant) reflector based on the „ELMI" accelerator (CST Studio Suite code): high-mode generation within a certain time interval (oversize parameter $l_x/\lambda \sim 7$).

An advanced Bragg structure [11] (Fig. 1) is installed at the oscillator input. This structure is a section of a planar waveguide with shallow corrugation

$$a = a_{adv}\cos(h_{adv}z) \quad (4)$$

($h_{adv} = 2\pi/d_{adv}$, d_{adv} and a_{adv} are the corrugation period and amplitude). Under resonance conditions

$$h \approx h_{adv} \quad (5)$$

this corrugation provides coupling and mutual scattering of two partial wave fluxes of type (2) and quasi-cutoff wave

$$\mathbf{E} = \mathbf{E}_B \mathrm{Re}\left[Be^{i\omega t}\right] \quad (6)$$

It is important to stress that, unlike „traditional" Bragg structures based on the coupling of two counter-propagating paraxial waves [13–15], the advanced Bragg reflector does not support direct mutual scattering of counter-propagating wave beams A_+ and A_-; scattering is effected only through the excitation of quasi-cutoff wave beam B. As in gyrotrons, the inclusion of a quasi-cutoff wave in the feedback loop allows one to rarefy significantly the spectrum of eigenmodes of Bragg structures of this type with considerable oversize parameter values and increase their selectivity in comparison with „traditional" counterparts. The operability and high selectivity of advanced Bragg structures with oversize parameter $D/\lambda \sim 45$ have already been demonstrated at frequencies up to 0.7 THz [16].

In the proposed design, the advanced structure acts as an effective narrow-band reflector with a Bragg reflection band narrower than the frequency interval between the slow-wave structure eigenmodes. Single-mode oscillation at a mode with a certain" transverse index along „wide' coordinate x (in a planar system) or a certain azimuthal index (in a cylindrical system) and its frequency falling within the reflection band of a resonant reflector may then be established in an SWO.

It should be noted that the proposed mode selection mechanism is an evolution of the approach detailed in [17,18]. However, the capacity for operation with oscillators of a significantly larger transverse size is an undoubted advantage of advanced Bragg structures over resonant reflectors in the form of a choke groove that were examined earlier.

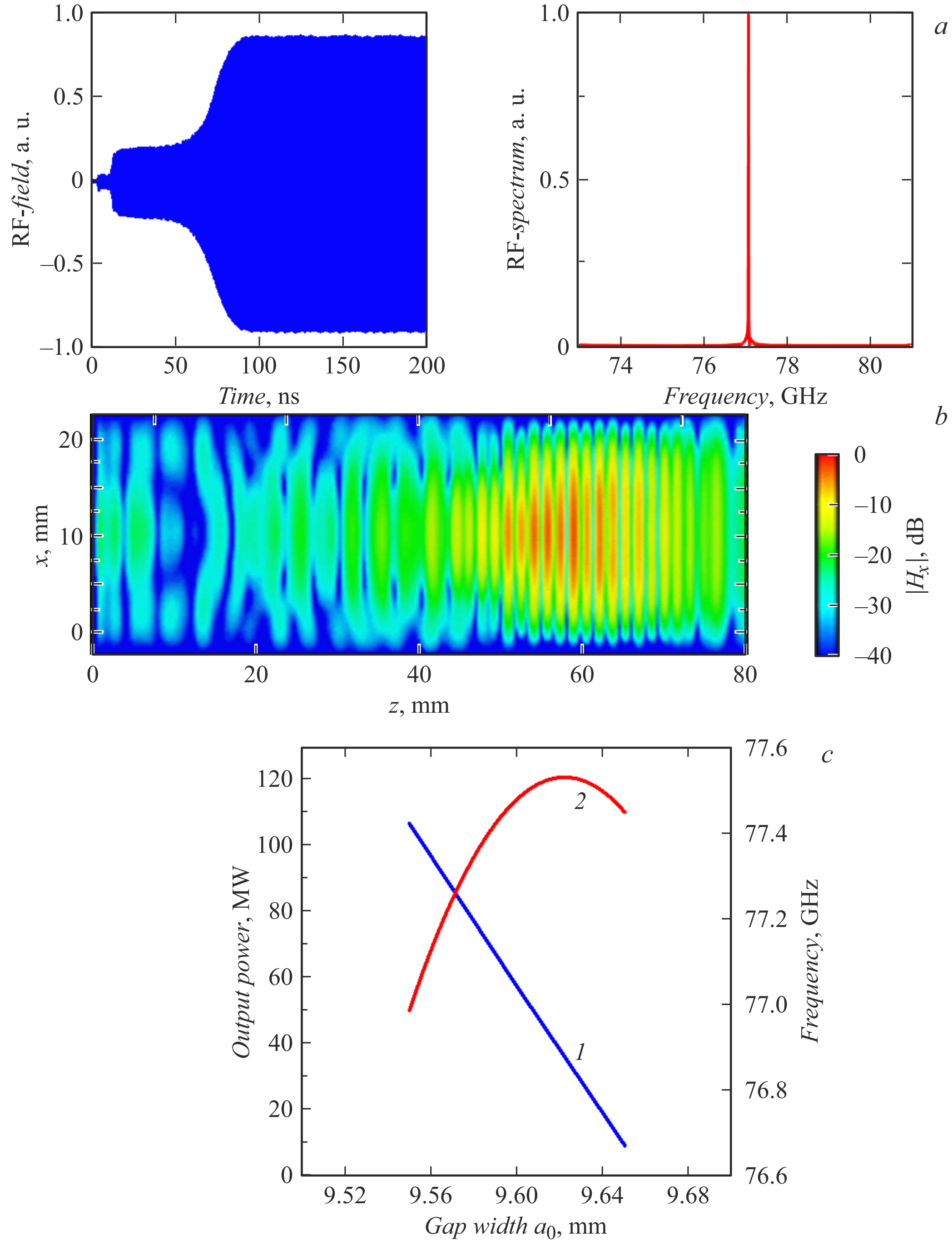

Figure 3. Results of modeling of a W-band surface-wave oscillator with an advanced resonant Bragg reflector based on the „ELMI" accelerator (CST Studio Suite code): transition to steady-state oscillation at the lowest mode of the slow-wave structure. *a* —Time dependence of magnetic field component H_x at the oscillator output (left) and radiation spectrum (right); *b* — RF field structure in the steady-state regime; and *c* — generation frequency tuning (curve *1*) and output power variation (curve *2*) with a change in gap size a_0 of the planar system (oversize parameter $l_x/\lambda \sim 7$).

The feasibility of application of advanced Bragg reflectors in planar SWOs was investigated through numerical modeling in the three-dimensional CST Studio Suite package. Modeling parameters close to the conditions of experiments conducted in collaboration between the Budker Institute of Nuclear Physics (Novosibirsk) and the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod) at the „ELMI" accelerator complex [19] were chosen. A slow-wave structure for W-band operation (an operating frequency of ~ 77 GHz) with a cross section of 10×28 mm (i.e., $\sim 2.5\lambda \times 7\lambda$) and length $l_{1D} \approx 35$ mm was designed. The period and amplitude of

1D corrugation on one of the plates of the planar waveguide were $d_{1D} \approx 1.55$ mm and $a_{1D} \approx 0.3$ mm, respectively. The advanced Bragg reflector had corrugation with period $d_{adv} \approx 4$ mm and amplitude $a_{adv} \approx 0.2$ mm that formed a feedback loop containing two counter-propagating wave beams of the lower TEM type and a quasi-cutoff wave beam of the TM_5 type; the length of the structure was $l_{adv} \approx 40$ mm. A 700 keV/1 kA/3 μs sheet REB with a cross section of 0.5×20 mm focused by a ~ 1.5 T guiding magnetic field was proposed to be used to drive the oscillator. The formation of spatially extended sheet REBs with parameters acceptable for efficient operation of relativistic W-band oscillators has been demonstrated in a series of preliminary electron-optical experiments at the „ELMI" accelerator complex (see [19] for details).

Two SWO designs with identical parameters were compared in our simulation. In the first design, a broadband mirror was installed at the input of the system; in the second one, a narrow-band resonant reflector with the above parameters was used.

The obtained data reveal multistable generation, which is characterized by the excitation of a large number of modes with different transverse indices and random phases, in the design without the resonant reflector. Figure 2 presents the operating regime in which oscillation at a mode with four variations of the RF field along „wide" transverse coordinate x proceeds within a certain time interval.

According to the simulation results, the use of the narrow-band advanced Bragg reflector leads to stable lowest-mode generation with one field variation along the longitudinal z and transverse x coordinates (Figs. 3, a, b). At optimum parameters, the electron efficiency reaches 15% in this case, which corresponds to an output power up to 120 MW.

The possibility of smooth tuning of the radiation frequency by adjusting gap size a_0 of the planar system (which leads to a change in cutoff frequency of feedback wave B in the advanced Bragg structure) is an additional advantage of the proposed generator design. The simulation reveals (Fig. 3, c) that the proposed planar SWO design provides a $\sim$ 1% tuning range for the generation frequency. However, this tuning is accompanied by a noticeable change in the electron-wave interaction efficiency (in the present simulation, the gap size was varied under constant REB parameters).

Thus, the results of theoretical analysis and three-dimensional modeling confirmed the operability and good application prospects of a new resonant Bragg reflector type that ensures stable narrow-band oscillation at a specific operating mode in SWOs based on one-dimensionally periodic slow-wave structures with significant oversize parameter values. The transverse extension of the structure opens up opportunities for increasing the integral oscillator power while maintaining moderate current densities and wave fluxes. The discussed design of a planar W-band oscillator is currently being implemented at the „ELMI" accelerator.

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Conflict of interest

The authors declare that they have no conflict of interest.

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