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Electrodynamic System of a Powerful THz Band Free Electron Laser Based on the LIU Linear Induction Accelerator: Modeling and Cold Tests

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Abstract—The authors describe the current stage of the development of a powerful long-pulse free electron laser (FEL) of the terahertz band at the Budker Institute of Nuclear Physics in cooperation with Institute of Applied Physics on the basis of the LIU induction accelerator with an energy of 5–10 MeV, a current of up to 2 kA, and a pulse duration of up to 200 ns. It is proposed that two alternative types of electrodynamic systems may be used to ensure a regime of stable narrow band generation: advanced Bragg resonators and quasi-optical resonators of the Talbot type. FEL parameters calculated on the basis of these resonators are presented, along with results from modeling under conditions of substantial oversize. The operability of the new types of resonators is verified in cold electrodynamic tests.

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INTRODUCTION

The family of LIU linear induction accelerators developed at the Budker Institute of Nuclear Physics (Novosibirsk) [1, 2] can generate relativistic electron beams (REBs) with energies of 5–10 MeV, currents of 1–2 kA, and pulse durations up to 200 ns. The use of such beams in an FEL allows us to generate radiation in the sub-terahertz (sub-THz) and terahertz (THz) frequency bands with power around 0.1–1 GW and a record enrgy content in pulses up to 10–100 J [3, 4].

A project for developing a powerful long-pulse FEL of the sub-THz/THz bands on the basis of the LIU accelerator is currently under way at the Budker Institute of Nuclear Physics in Novosibirsk, in cooperation with Institute of Applied Physics in Nizhny Novgorod. A series of electron optical experiments ensured the generation of REBs with parameters required for efficient operation of the generator in the above bands and their transport across the generator's vacuum system [5]. The achieved transverse beam size (diameter) in the zone of FEL operation is $D_{\text{beam}} \sim 7$–10 mm.

For the transmission of the intense REBs generated by the LIU (allowing for the amplitude of bounce oscillations of electrons in an undulator) over the space of FEL interaction, the diameter of the system should be $D \geq 15$–20 mm. This exceeds the wavelength of radiation in the considered bands by several orders of magnitude. A key problem in obtaining an FEL is therefore developing an electrodynamic system capable of ensuring a steady regime of narrow band generation under conditions of substantial oversize of the space of interaction. To solve the problem of selecting a mode of operation under similar conditions, the development project is considering two main types of electrodynamic systems: (1) advanced Bragg resonators that ensure the interrelation between traveling and quasi-cutoff waves, and (2) quasi-optic resonators based on the Talbot effect. In this work, we consider design features of these resonators, their electrodynamic properties, and results from cold tests in the sub-THz frequency bands. Results from modeling the FEL are presented using these resonators under conditions of substantial oversize of the space of interaction.

AN FEL BASED ON ADVANCED BRAGG RESONATORS

A specific feature of advanced Bragg resonators is the feedback of quasi-cutoff waves in the circuit [6]. An advantage of such structures is much higher selectivity than that of conventional analogs based on the interrelation of two travelling paraxial waves [7, 8]. In contrast to conventional analogs, there is no direct interrelation between propagating and counter propagating waves in an adbanced Bragg structure. It arises only due to the excitation of quasi-cutoff waves. Including the feedback (e.g., gyrotrons) from the cutoff wave in the circuit [9] allows us to rarefy the spectrum of the resonator mode. Under conditions of substantial oversize $D/\lambda \gg 1$, the density of the spectrum of cutoff waves is much lower than that of paraxial waves that determine the feedback cycle in conventional Bragg resonators. This greatly improves the selective properties of advanced Bragg structures, relative to their conventional analogs. At the same time, interaction with intense REBs in an FEL is ensured by a propagating synchronous wave under conditions of a large Doppler frequency up-conversion. An FEL based on advanced Bragg resonators therefore allows us to combine the advantages inherent in gyrotrons (high selectivity in terms of the transverse index of modes) and relativistic generators (the ability to operate in short wave bands at high levels of pulse power). According to modeling done on the basis of both averaged models and 3D PIC codes, advanced Bragg structures ensure selective excitation of the operating mode at transverse sizes of the space of interaction up to $D/\lambda \sim 50$ wavelengths, which would seem to be enough for creating channels of the transportation of intense REBs up to THz band [10, 11].

The operability of advanced Bragg resonators was confirmed experimentally in FEM prototypes developed by the Institute of Applied Physics in cooperation with the Joint Institute for Nuclear Research in Dubna, on the basis of the LIU-3000 accelerator with 0.8 MeV/200 A/200 ns. The use of a new type highly selective Bragg resonators in these experiments allowed us to obtain steady narrow band generation up to the W band of frequencies at oversize of $D/\lambda \sim 5$ and MW levels of power [12]. It should be noted that the generation of narrow bands in the main mode has been observed in over the band of the zone of self excitation in an FEM developed on the basis of advanced Bragg resonators upon varying the amplitude of the undulator's field (and correspondingly detuning the synchronism of electrons with the operating wave), testifying to the stability of the working regime with respect to changes in beam parameters. In earlier experiments [13], jumps in the frequency of generation corresponding to the excitation of different pairs of waveguide modes were observed in an FEM with conventional Bragg resonators upon similar changes in the field of the undulator at system oversize of only $D/\lambda \sim 2$.

A further increase in the FEM frequency of generation at the Institute of Applied Physics and Joint Institute for Nuclear Research was limited by the feasible periods of the undulator and the energy of the electron beam generated by the LIU-3000 accelerator. At the same time, this type of generator can be converted to the region of terahertz frequency on the basis of more powerful LIU accelerators developed at the Budker Institute of Nuclear Physics [1, 2]. However, the operation of powerful FEL generators in high frequency bands inevitably requires an increase in the oversize of the space of interaction. This is needed to create a channel for the transport of intense REBs on one hand, and to reduce the ohmic loss on the other.

To solve this problem, we studied the possibility of creating in the sub-THz/THz band resonators based on advanced Bragg structures with oversize an order of magnitude higher than the wavelength or more. At this stage, advanced Bragg structures were developed for an FEL operating in the 0.7 THz band (Fig. 1a). These structures had diameter $D \approx 20$ mm ($D/\lambda \sim 45$), lengths around 5 cm, corrugation with a period of 0.43 mm, and a depth of 0.15 mm, ensuring feedback cycle $TE_{1,1} \leftrightarrow TE_{1,45} \leftrightarrow TE_{1,1}$. Three-dimensional modeling with the CST Microwave Studio code showed that even at such large transverse sizes advanced Bragg structures ensure selective reflection of the operating wave with an efficiency of ~90% in terms of power. Cold electrodynamic tests confirmed the results from modeling and the existence of efficient narrow band reflection in the calculated band of frequencies (Fig. 1b). It should be noted that the described prototype Bragg structures were developed using a new additive technology of photopolymer 3D printing with the subsequent chemical application of a copper layer [14].

Results from modeling a Bragg FEL generator based on an LIU accelerator with 5 MeV/2 kA in the THz band are presented in Fig. 2. Modeling was done with original averaged 3D quasi-optical models of electron wave interaction, within the framework of the coupled wave method with parameters close to the conditions of planned experiments. The original magnetic system of this FEL included a pulsed helical undulator with a period of 4 cm for exciting operating bounce oscillations of electrons and solenoids to create a guiding longitudinal magnetic field of ~0.4 T (in the so-called reverse configuration) for the focusing and transpiration of intense REBs [5]. It has been proposed that a two-mirror resonator be used as the electromagnetic system of an FEL in which advanced Bragg structures act as efficient selective reflectors. Modeling showed the sectioning of the space of interaction provided by the two-mirror design of the resonator is attractive in terms of reducing the ohmic loss at high frequencies and improving the efficiency of the generator.

The two-mirror resonator for operating an FEL at a frequency of ~1 THz was designed with diameter $D \approx 12$ mm (oversize $D/\lambda \sim 40$), a regular section around 50 cm long, and Bragg structures (reflectors) 20 cm (up-stream) and 12 cm (down-stream) long, having corrugation with a period of 0.3 mm and depths of ~20–30 μm. Modeling showed that (Fig. 2) the electron efficiency could be as high as 2–3% at the calculated parameters, with an output power of 0.2–0.3 GW. The ohmic loss was no more than 25–30% of the radiated power. It should be noted that moving to

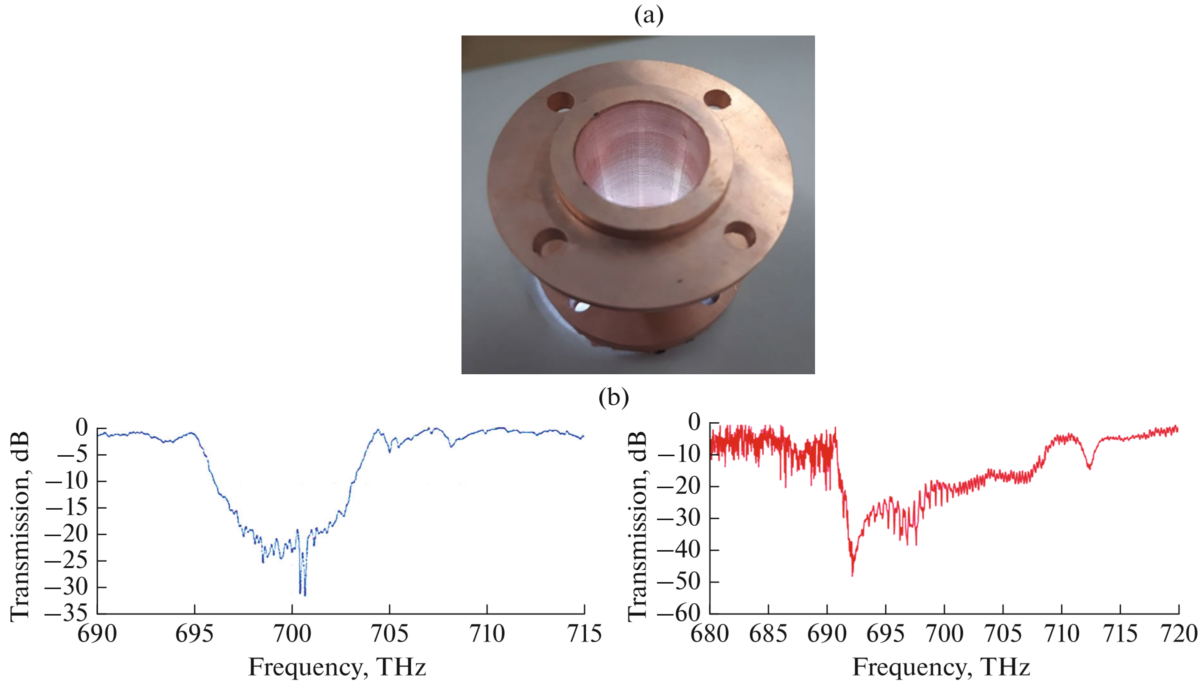

Fig. 1. (a) Prototype of a advanced Bragg structure in the 0.7 THz band and (b) results from its 3D modeling (left) and cold tests (right). The coefficient of transmission is given as a function of frequency.

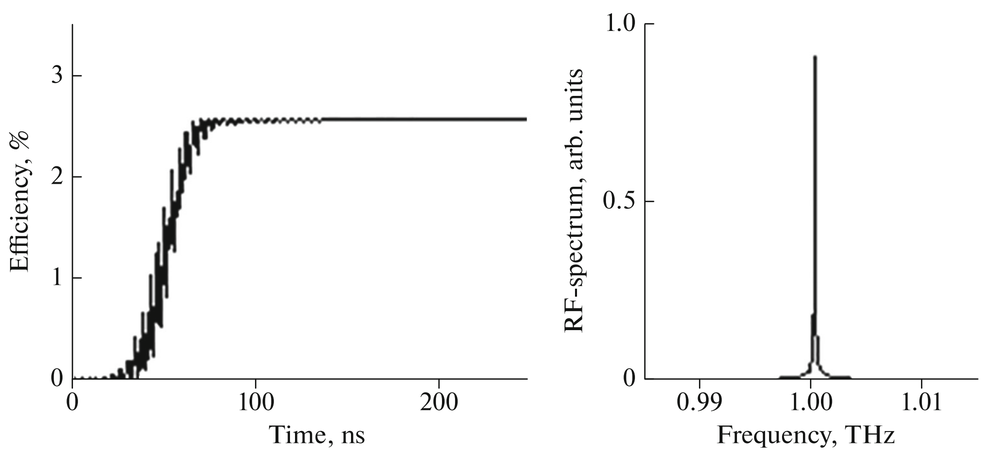

Fig. 2. Results from modeling an FEL with a two-mirror resonator, based on advanced Bragg structures powered by the LIU accelerator in the 1 THz band. The electron efficiency is given as a function of time (left) and the spectrum of the frequency of radiation (right).

schemes of resonators open in the transverse direction (e.g., planar systems and waveguides with lateral sections) are thought to be promising for operating in the high-frequency band, which (as our theoretical analysis showed) allows us to rarefy even more the density of the spectrum of transverse modes and thus improve their selective properties.

A FEL WITH TALBOT-TYPE RESONATORS

Quasi-optical resonators based on the Talbot effect would seem to be a promising alternative type of electrodynamic system [15, 16]. As an expansion of this concept in the FEL project, we are studying the possibilities of the simplest resonator (in terms of technology) formed by a section of a plain oversized cylindrical waveguide with two rings at the edges acting as mirrors where there is periodic reproduction of the transverse structure of wave beam as a consequence of the Talbot effect [17, 18]. The concept of such a resonator is based on rejecting the excitation of a fixed transverse mode and moving to excitation of the so-called supermode formed by a fixed set of several transverse modes of an oversized waveguide with the same frequency.

(a)

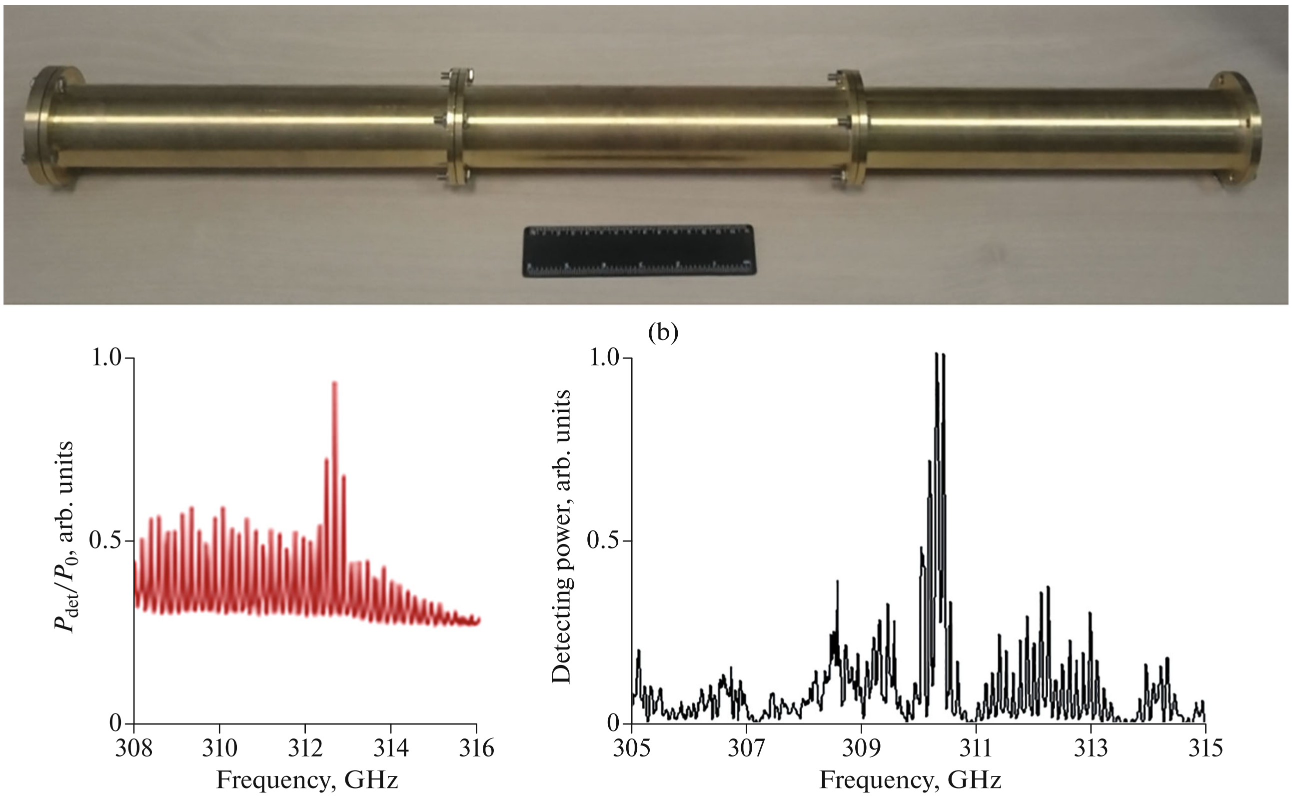

Fig. 3. (a) Prototype resonator based on the Talbot effect in the 0.3 THz range, and (b) its modeling (left) and cold tests (right). The signal power is given as a function of frequency detected in the coupling hole.

A prototype resonator based on the Talbot effect with a diameter of 36 mm ($D/\lambda \sim 40$) and a length of ~80 cm for operating in the ~0.3 THz band of frequencies was designed in order to perform cold tests (Fig. 3a). The mirrors (rings) positioned at the edges were 4 mm wide, and the output mirror had a coupling hole 2 mm in diameter (the position of the aperture corresponded to that of the calculated maximum of the field). The resonator was exited from the resonator input side by a wave of the $TE_{1,1}$ type. Modeling showed this wave is effectively transformed into one of the $TE_{1,7}$ type, which is present most in the supermode at operating frequency. The output signal was detected over the coupling hole. Modeling showed the peak power should be observed in the coupling hole at the frequency corresponding to the sought supermode. A well-pronounced peak of the detected output power at the designed frequencies was observed in our cold tests, in accordance with the results from modeling, confirming the operability of a resonator of this type (Fig. 3b).

In modeling, we studied the possibility of developing an FEL in the frequency band of ~2 THz, based on the 7 MeV/1.5 kA beam generated by the LIU accelerator. A resonator of the Talbot type with diameter $D \approx 10.5$ mm ($D/\lambda \sim 70$) and a length of ~60 cm was considered as an electromagnetic system for this FEL. According to results from design (Fig. 4), the electron efficiency at the calculated parameters is around 5%, which corresponds to an output radiation power of 0.5 GW. The transition takes ~80–100 ns (i.e., around 20 transits of the wave along the resonator).

CONCLUSIONS

Our theoretical and experimental studies confirm the promise of developing powerful long-pulse FEL generators based on the LIU linear induction accelerator at the Budker Institute of Nuclear Physics and operating in the sub-THz/THz band. New and highly selective resonator schemes were proposed for this FEL: advanced Bragg resonators and quasi-optical resonators based on the Talbot effect. Cold electrodynamic tests showed the feasibility and operability of such resonators under conditions of substantial oversize. Modeling demonstrated the effectiveness of using them to ensure a regime of steady narrow band generation in FELS based on the LIU accelerator: advanced Bragg resonators from the sub-THz to the THz band at oversize up to 40–50 wavelengths and resonators of the Talbot type at frequencies up to 2–5 THz when $D/\lambda \geq 100$. The power of radiation can reach the sub-GW level with energy content in pulses of ~10–100 J.

Key components of the electrodynamic system have been manufactured, and a prototype FEL gener-

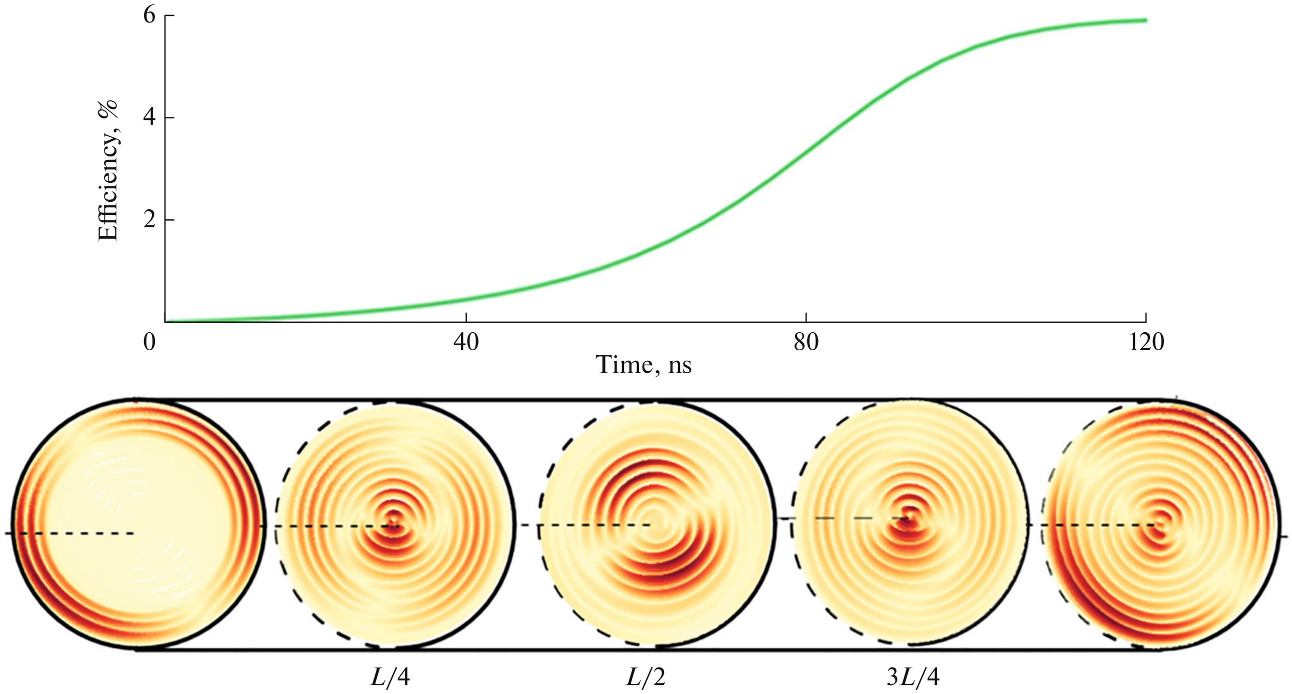

Fig. 4. Results from modeling an FEL with a resonator of the Talbot type, based on the LIU accelerator in the 2 THz band. The electron efficiency is given as a function of time (above) and the transverse structure of an excited wave beam in different transverel cross sections of the resonator in the steady regime (below).

ator is now being assembled at the LIU accelerator. Electron optical experiments have been performed on creating REBs with the required parameters, injecting them, and transporting them through the space of interaction. The initial experiments to test the operation of the FEL at the designed power levels are planned to start in the range of 0.6–0.7 THz, with the possibility of prospect to higher frequency bands if positive results are obtained.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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