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DEVELOPMENT OF POWERFUL LONG-PULSE TERAHERTZ BAND FELS BASED ON LINEAR INDUCTION ACCELERATORS*

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Abstract

The paper is devoted to development of high-power long-pulse THz-band FELs based on the new generation of linear induction accelerators elaborated recently at Budker Institute (Novosibirsk). These accelerators generate microsecond electron beams with a current at kA-level and an energy of 2 to 5 MeV (with a possibility to increase the electrons energy up to 20 MeV). Based on this beam, we initiated a new project of multi-MW long-pulse FEL operating in the frequency range of 1 to 10 THz using a wiggler period of 3 to 6 cm. For this FEL oscillator, we propose a planar two-mirror resonator comprising highly selective advanced Bragg reflectors. Alternately, electrodynamic system for oscillators of this type can use hybrid two-mirror resonator consisting of an upstream advanced Bragg reflector and a downstream weakly reflecting conventional Bragg reflector. Simulations demonstrate that the advanced Bragg reflector based on coupling of propagating and quasi-cutoff waves ensures the mode control at the values of the gap between the corrugated plates forming such a resonator of up to 20 wavelengths. Simulations of the FEL driven by electron beam generated by the LIA-2 in the frame of both averaged approach and 3D PIC code demonstrate that the THz radiation power can reach the level of 10 to 20 MW.

INTRODUCTION

Distributed feedback based on periodic Bragg structures is widely used in classical and quantum generators of coherent radiation. Correspondingly, the frequency band of oscillators with this feedback mechanism covers the millimeter and optical (infrared) bands [1–3]. Use of Bragg mirrors in X-ray lasers was discussed in multiple works (for example, [4]). In the present paper, we show that the advanced Bragg structures can be efficiently used in terahertz free-electron lasers. In addition to the compatibility with the transport channels of intense electron beams, the advantage of the proposed structures is the spatial coherence of radiation at large values of the oversize factor of the interaction region with respect to both transverse coordinates.

Scheme of a planar FEL under consideration is shown in Fig. 1. A feature of this scheme is the use of Bragg mirrors coupling the longitudinal and transverse (with respect to the velocity of the particles) wavebeams.

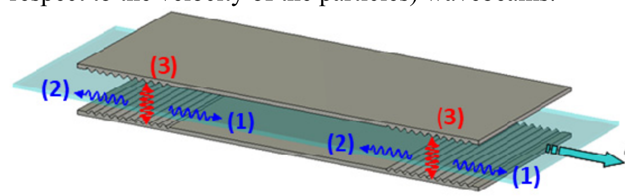

Figure 1: Scheme of FEL with two-mirror advanced Bragg resonator. Arrows (1), (2) indicate propagating of paraxial waves, (3) – quasi-cutoff feedback wave.

TUNABLE TERAHERTZ BRAGG REFLECTORS BASED ON COUPLING OF PROPAGATING AND CUTOFF WAVES

Bragg reflectors in the form of corrugated waveguide sections were proposed in [2] and are widely used currently as elements of electrodynamical systems in relativistic masers [3]. An obvious advantage of such systems is the compatibility with transportation of a high-current relativistic electron beam. Similarly to their optical prototypes, conventional variants of Bragg structures provide coupling and mutual scattering of the two counter-propagating paraxial waves. In the experiments on generation of radiation in the long wavelength part of the millimeter wavelength band, usual diameter of such cavities is restricted by size of several wavelengths.

In order to advance the relativistic masers into the sub-millimeter wavelength band, an increase in the oversize parameter of the cavities is required. However, this leads to a dramatic reduction in selectivity of the resonators composed from conventional Bragg structures due to overlapping of the reflection zones for different waveguide modes. Besides, a significant drop of the absolute values of the reflection coefficient of such structures takes place.

This problem can be solved using advanced Bragg structures based on coupling of propagating and quasi-cutoff waves. Similarly to sub-millimeter wave gyrotrons, the inclusion of the cutoff wave into the feedback loop leads to mode spectrum purification because the frequency interval between the cutoff waveguide modes is much higher than that between the paraxial waves. As a result, an advanced Bragg structures can be efficiently used as a narrow band reflector in the long-pulse THz-band FELs.

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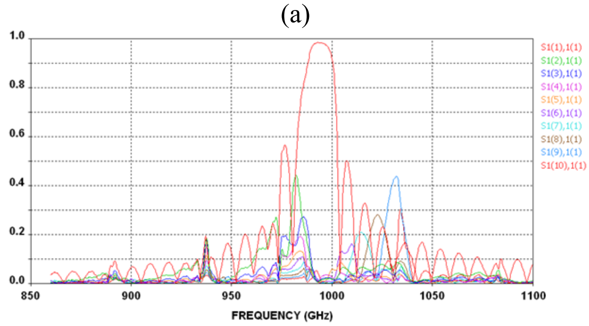
A planar advanced Bragg reflector is formed by two metal plates with a sinusoidal corrugation [5]. Under the Bragg resonance conditions, this structure provides coupling of two counter-propagating waves via excitation of a cutoff mode. As a result, advanced Bragg structures possess a narrow-band reflection zone near the cutoff frequency of the quasi-cutoff mode. It is important to note that the period of an advanced Bragg structure is approximately two times longer than the period of a conventional one, which is obviously beneficial in short-wavelength bands in terms of the manufacturing process. Another advantage of the advanced Bragg structure is the tunability of the reflection zone. At moderate values of the transverse size, variation of the distance between the plates is accompanied by a relatively wide shift of the reflection zone following the change in the cutoff frequency. At the same time, the reflection coefficient has rather small change for structures with optimal geometry.

Simulations of the advanced Bragg reflector (Fig. 2a) were carried out using the 3D code *CST MICROWAVE STUDIO*. The advanced Bragg reflector was composed of two parallel copper plates with a length of 20 cm, the period and depth of corrugation were 0.3 mm and 15µm, correspondingly. Such structure provides resonance coupling of the propagating TEM waves and the quasi-cutoff mode of TM_{40}-type at the gap of 6 mm.

The result of the simulation of an advanced Bragg structure is shown in Fig. 2a. At such a large oversize parameter it sustains the reflectivity at the high level (power reflection more than 90%). For comparison, the properties of a conventional Bragg reflector of the same dimensions were studied (see Fig. 2b).

(a)



(b)

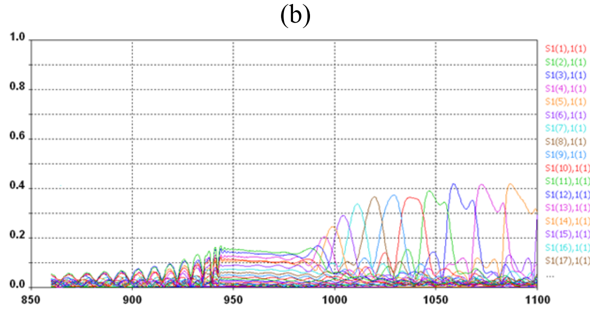


Figure 2: 3D simulations of Bragg resonators at THz-band using using *CST MICROWAVE STUDIO* software. (a) Advanced Bragg reflector, (b) conventional Bragg reflector.

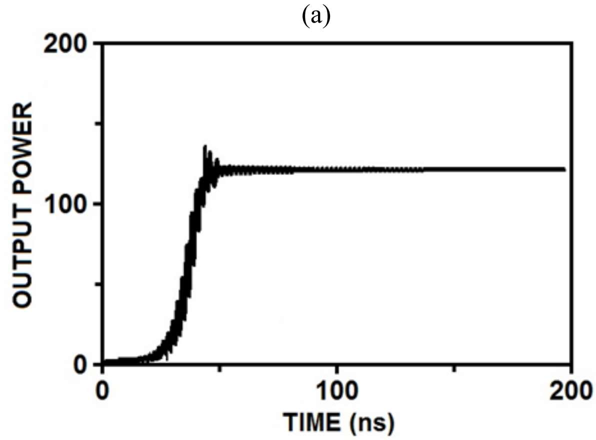
PROJECT OF POWERFUL BRAGG FEL FOR THz-BAND

The basis of the project is powerful induction linac elaborated recently at BINP RAS (the LIA-2 accelerator) [6]. This accelerator generates an electron beam with a current at kA-level and energy of 2 - 5 MeV (with the possibility to increase electrons energy up to 20 MeV).

Based on this beam, we initiated a new project of multi-MW long-pulse THz FEL. In fact, the use of the beam with specified particles energy allows for a realization of the FEL in the range of 1 - 10 THz using the wiggler with a period of 3 to 6 cm. For the realized beam current of ~ 1 - 2 kA, the radiation power is estimated on the level of 10 - 100 MW even while the electron efficiency remains rather low, about 1 to 0.1% (which, obviously, would decrease with increase of the radiation frequency).

Results of simulation of the FEL driven by a 5 MeV / 1 kA electron beam generated by the LIA – 2 are presented in Fig. 3. This beam is focused by the guide magnetic field of ~ 0.15 T (in reversed configuration) and operating transverse electron velocities in the beam are pumped by the wiggler having 4 cm spatial period. For this FEL-oscillator we consider two-mirror resonator consisting of advanced Bragg reflectors of planar geometry (see Fig.1).

(a)



(b)

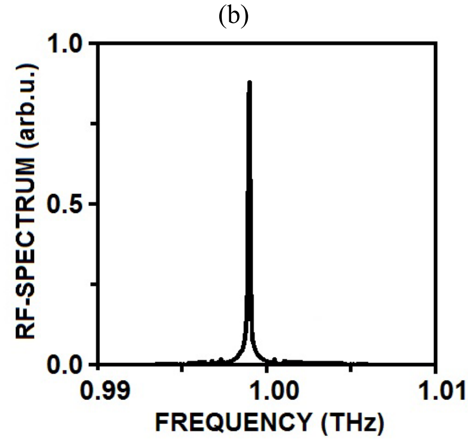


Figure 3: Results of simulations of FEL – oscillator in the frame of averaged theory. (a) Establishment of stationary narrow-band oscillation regime, (b) radiation spectrum.

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Simulations demonstrated that Bragg structures of such type possess high reflectivity and ensure selectivity of the resonator for the transverse size (gap) up to 20 wavelengths. This size is sufficient for usage with the intense relativistic electron beams. For operation at 1 THz, we designed the resonator with a 6 mm gap and the Bragg structures 20 cm (up-stream) and 10 cm (down-stream) long having corrugation of the 0.3 mm period and 10 – 15 μm depth, a regular section of 50 -70 cm long between them. According to the simulations, under designed parameters the electron efficiency could reach 2 to 3% and the output power is 50 to 100 MW. The Ohmic losses in this case do not exceed 25 - 30% of the radiated power.

In summary, a novel concept of high-power THz-band Bragg FEL was developed. Original feature of this concept (in comparison with the others for now operating THz FEL) is the possibility to use electron beams with high-current (kA-level) and long-pulse (hundreds ns) duration. Such beams would allow achieving record levels of the radiation power of 10 - 100 MW and pulse energy up to 10 J for the THz-band. Operability of key components of electrodynamic system for such FEL, namely, the advanced Bragg resonators, was demonstrated in the proof-of-principle experiments in terahertz band at the oversize parameter of Ø/λ ~ 7.

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