PRODUCTION OF POWERFUL SPATIALLY COHERENT RADIATION IN FREE ELECTRON LASERS BASED ON TWO-DIMENSIONAL DISTRIBUTED FEEDBACK*

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Abstract

For intense oversize relativistic electron beams with sheet and annular geometry the use of two-dimensional (2D) distributed feedback is beneficial for providing spatial coherence of the radiation and, thus, can be used to increase the total radiation power. Such 2D feedback can be realized in planar and co-axial 2D Bragg resonators having double-periodic corrugations of the metallic side walls. Modelling of the nonlinear dynamics of the FEL with 2D distributed feedback demonstrated the advantages of the novel feedback mechanism for production of spatial coherent radiation from large size electron beams. Simulation results are confirmed by recent experimental results where narrow frequency radiation was obtained at Ka-band co-axial and W-band planar 2D Bragg FELs which were realized at the Strathclyde University and Budker INP RAS.

INTRODUCTION

Two-dimensional (2D) distributed feedback [1, 2], which is realized in Bragg resonators having double-periodic shallow corrugation in two perpendicular directions, is an effective method of producing spatially coherent radiation in relativistic masers driven by large-size electron beams of sheet and annular geometry. This mechanism can be considered as a development of 1D distributed feedback based on the traditional single-periodic Bragg structures, which are widely used currently in classical and quantum electronics. By spatially-extending over one of the transverse coordinates of the interaction space allows a significant increase of the total microwave power (up to GW powers) while keeping the power and current densities at a moderate level. The novel feedback mechanism is attractive for use from microwave to THz frequencies as well as in quantum lasers.

Experimental studies of FELs based on this novel feedback mechanism are performed in W-band (planar geometry) at the Budker INP RAS (Novosibirsk) [3, 4] and in the Ka-band (coaxial geometry) at the University of Strathclyde (Glasgow) [5] in collaboration with the IAP RAS (N.Novgorod) and University of Karlsruhe. As a result of this work narrowband microwave generators of multi-MW power level were realized. In these experiments effective mode selection over the transverse (azimuthal) index was demonstrated with an oversize parameter of the resonators of about 25 wavelengths. The present paper is devoted to the results of simulations and experimental studies of these two types of FELs.

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PLANAR 75 GHz FEL WITH HYBRID BRAGG RESONATOR

The 2D distributed feedback is based on the mutual scattering of the four partial wave fluxes

$$\vec{E} = \vec{E}_0 \,\mathrm{Re}\left\{\left[\mathrm{A}_+ e^{-ihz} + \mathrm{A}_- e^{ihz} + \mathrm{B}_+ e^{-ihx} + \mathrm{B}_- e^{ihx}\right] e^{i\bar{\omega}t}\right\}, \quad (1)$$

where two fluxes ($\mathrm{A}_\pm$) propagate in forward and backward (with respect to the electron beam propagation) $\pm z$ directions and two other fluxes ($\mathrm{B}_\pm$) propagating in the transverse $\pm x$ directions act to synchronize different parts of the sheet electron beam. This scattering scheme is realized at planar 2D Bragg structures having double-periodical corrugation of the metal plates.

$$a = \frac{a_{2D}}{4}\left[\cos \bar{h}_{2D}(z-x) + \cos \bar{h}_{2D}(z+x)\right], \quad (2)$$

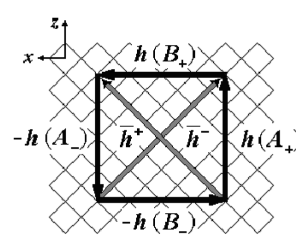

Figure 1: Diagram illustrating the scattering of the partial waves at the 2D Bragg structure

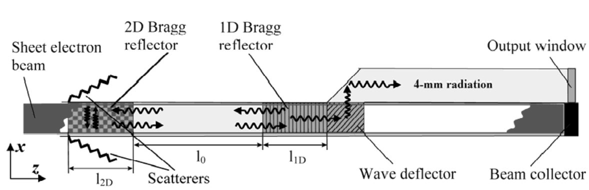

Figure 2: Schematic layout of the 75-GHz planar FEL exploiting 2D distributed feedback.

where a_{2D} is the corrugation depth ($a_{2D} << a_0$, $a_{2D} << \lambda$ and a_0 is the mean separation of the waveguide plates). The efficient scattering of partial waves (1) takes place under the Bragg resonance condition (Fig.1)

$$h \approx \bar{h}_{2D}. \tag{3}$$

where h is the wavenumber, $\bar{\omega} = c\bar{h}_{2D}$ is the Bragg frequency, $\bar{h}_{2D} = 2\pi/d$ and d is the corrugation period over the diagonals.

In this section we describe the results of investigations of a 75 GHz planar structure. To demonstrate the operability of novel feedback mechanism, modelling of a sheet beam with a transverse size of about 20 wavelengths was used. The schematic diagram of the experimentally studied planar FEL is shown in Fig.2. The electrodynamic system of the generator is a hybrid resonator consisting of two Bragg structures with different operating features: up-stream (cathode-side) 2D Bragg reflector and down-stream (collector-side) traditional 1D Bragg reflector The spatial synchronization of radiation in the transverse (x) direction is achieved in the input 2D Bragg reflector due to the above-described scheme of coupling of four partial waves (1). Interaction with the magnetically-guided electron beam oscillating in the planar wiggler mainly takes place in the regular part of the resonator, where the synchronous wave A_+ is amplified by the electrons. A conventional 1D Bragg mirror at the output of the system reflects a small amount of the RF-energy into the backward direction, thus forming the feedback loop and providing the conditions for self-excitation of the generator.

In the frame of the coupled-waves approach the dynamics of the FEL with 2D distributed feedback can be described by the system of equations for the partial waves amplitudes $A_\pm$ and $B_\pm$ [2, 3]:

$$\begin{aligned}
&\left(\frac{\partial}{\partial Z} + \beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_+ + i\alpha_{2D}\left(B_+ + B_-\right) = J \\
&\left(\frac{\partial}{\partial Z} - \beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_- + i\alpha_{2D}\left(B_+ + B_-\right) = 0\ . \\
&\left(\frac{\partial}{\partial X} \pm \beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)B_\pm + i\alpha_{2D}\left(A_+ + A_-\right) = 0
\end{aligned} \tag{4}$$

The forward wave A_+ is excited by the beam. The RF-current in (4) $J = \frac{1}{\pi}\int_0^{2\pi} e^{-i\theta} d\theta_0$ can be found from the electron motion equations

$$\begin{aligned}
&\left(\frac{\partial}{\partial Z} + \beta_{\parallel}^{-1}\frac{\partial}{\partial \tau}\right)^2 \theta = Re\left\{A_+ e^{i\theta}\right\}, \\
&\theta\big|_{Z=0} = \theta_0 \in [0, 2\pi],\quad \left(\frac{\partial}{\partial Z} + \beta_{\parallel}^{-1}\frac{\partial}{\partial \tau}\right)\theta\big|_{Z=0} = \Delta
\end{aligned} \tag{5}$$

where θ is the electron phase.

The output traditional 1D Bragg reflector possesses single-periodical corrugation (Fig.2)

$$a = \frac{a_{1D}}{2}\cos(\bar{h}_{1D} z), \tag{6}$$

where a_{1D} is the corrugation depth, $\bar{h}_{1D} = 2\pi/d_{1D}$ and d_{1D} is the corrugation period. This structure provides mutual scattering of two counter-propagating partial waves $A_\pm$, which can be described by the equations

$$\begin{aligned}
&\left(\frac{\partial}{\partial Z} + \beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_+ + i\alpha_{1D}A_- = J \\
&\left(-\frac{\partial}{\partial Z} + \beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_- - i\alpha_{1D}A_+ = 0
\end{aligned}\ . \tag{7}$$

In Eqs.(4)-(7) the following dimensionless variables are used $Z = zC\bar{\omega}/c$, $X = xC\bar{\omega}/c$, $\tau = tC\bar{\omega}$, Δ is the initial mismatch of the electron-wave synchronism, $(A_\pm, B_\pm) = (A_\pm, B_\pm)\cdot ek\mu / \gamma mc\bar{\omega}C^2$, $k = \beta_\perp/\beta_\parallel$ is the electron-wave coupling parameter, $\mu \approx \gamma^{-2}$ is the inertial bunching parameter, C is the gain parameter, $\alpha_{2D} = a_{2D}/8a_0C$ and $\alpha_{1D} = a_{1D}/2a_0C$ are the wave coupling coefficients for 2D and 1D Bragg structures respectively.

Results of the simulation of the oscillations build-up for the microwave system geometry and the electron beam parameters close to the experimental conditions are shown in Fig.3 and demonstrate the establishment of a steady-state single-frequency regime. It is important to note that the synchronous partial wave A_+ in the steady-state regime has practically uniform field distribution over the x coordinate (see Fig. 3c) that ensures the same conditions for the energy extraction from all parts of the beam and, as a result, rather high electron efficiency can be achieved.

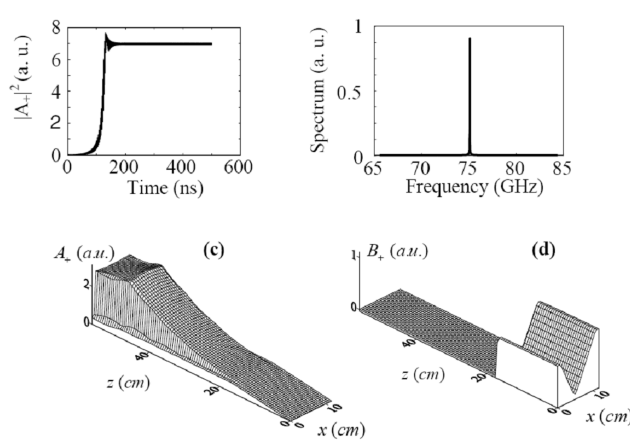

Figure 3: Simulation of synchronization in a planar FEL with hybrid Bragg resonator: (a) time dependence of the normalized output power $|A_+|^2$, (b) radiation spectrum and spatial profile of the partial waves (c) $|A_+|$ and (d) $|B_+|$ in the steady-state regime.

Experimental studies of the planar FEL with 2D distributed feedback was performed based on the high-current accelerator "ELMI" (BINP RAS, Novosibirsk) [4]. A sheet relativistic electron beam with the transverse cross-section 0.4×7 cm, electron energy 0.8 MeV and current up to 3 kA was generated in a sheet vacuum magneto-insolated diode and transported in a strong (up to 1.4 T) guide magnetic field inside a planar vacuum channel with the cross section 0.95×10 cm. The wiggler magnetic field had a spatial period of 4 cm and an amplitude of up to 0.2 T. The resonator was composed from the input 2D and output 1D Bragg reflectors and regular section of a rectangular waveguide of length $l_0 = 32$ cm (see Fig.2). The input reflector of length $l_{2D} = 19$ cm consisted of two copper plates with a chessboard corrugation with a depth of 0.02 cm and a spatial period of 0.4 cm along the x and z coordinates). The transverse energy fluxes in the 2D Bragg reflector were scattered outside the resonator by additional metal plates with irregular surface profiles. Since the radiation is amplified by the electron beam mainly after the two-dimensional mirror (see Fig.3c), the energy losses due to this scattering are rather small. The output Bragg reflector of length $l_{1D} = 19$ cm had a corrugation with a period of 0.2 cm and a depth of 0.007 cm. A Bragg deflector (see Fig.2) was used at the output of the Bragg resonator to direct the radiation into a parallel channel and to split the output radiation and the powerful electron beam traveling to the collector.

Microwave radiation was observed when the beam current exceeded 1 kA, which is in good agreement with the calculated starting current. A narrowband generation at a frequency close to the frequency of one of the eigenmodes of the hybrid Bragg resonator have been obtained for a large number of pulses (see Fig.4). In some other shots the generation at other frequencies, which corresponded to the excitation of different longitudinal modes of the resonator, was observed. According to the simulations, the possibility of excitation of different resonator modes is due to variations in the electron beam energy and beam current during the pulse, as well as pulse-to-pulse jitter. A total radiation power of about a few tens of megawatts was measured using the calorimeter and the calibrated hot-carrier detectors.

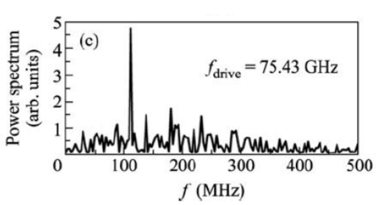

Figure 4: Radiation spectrum of the 75-GHz planar FEL.

MODELING AND EXPERIMENTAL STUDIES OF COAXIAL 37 GHZ FEL

In this section we consider a co-axial scheme of the FEL with a hybrid Bragg resonator (Fig.5) which is investigated experimentally at the University of Strathclyde [5-7]. The 2D Bragg structure represents a section of coaxial waveguide of length l_{2D}, the mean radius r_0 and having a corrugation in the form of two helices of opposite rotation

$$a = \frac{a_{2D}}{4}\left[\cos(\bar{h}_z z - \bar{M}\varphi) + \cos(\bar{h}_z z + \bar{M}\varphi)\right], \tag{8}$$

$\bar{h}_z = 2\pi/d_z$, d_z is the corrugation period along z axis, $\bar{M}$ is the azimuthal number of the corrugation, z and φ are the longitudinal and azimuthal coordinates respectively. We assume the waveguide to be of a small curvature, i.e. the waveguide radius is significantly larger than the radiation wavelength λ and the distance

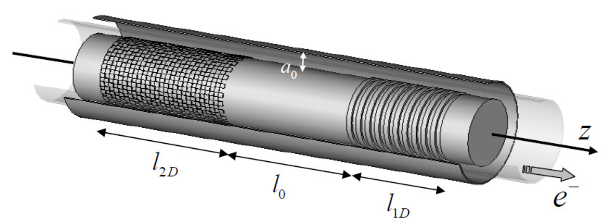

Figure 5: Scheme of interaction space of the FEL with a hybrid resonator consisting from 2D and 1D Bragg reflectors of coaxial geometry.

between the conductors a_0. The RF-field can be presented, similar to planar system, as a superposition of the four coupled waves propagating in the longitudinal $\pm z$ directions ($A_\pm$) and the azimuthal $\pm\varphi$ directions ($B_\pm$):

$$\vec{E} = Re\left\{\left[A_+\vec{E}_1^0 e^{-ih_1 z} + A_-\vec{E}_1^0 e^{ih_1 z} + B_+\vec{E}_2^0 e^{-ih_2 x} + B_-\vec{E}_2^0 e^{ih_2 x}\right]e^{i\bar{\omega} t}\right\},$$

$\vec{E}_{1,2}^0(r)$ are the functions specifying the radial structure of the waves, $x = r_0\varphi$ the coordinate along the waveguide azimuth. For the coaxial geometry the partial waves must obey the cyclic conditions

$$A_\pm, B_\pm(x + l_x, z, t) = A_\pm, B_\pm(x, z, t), \tag{9}$$

where $l_x = 2\pi r_0$ is the resonator perimeter. These conditions allow the Fourier expansion of the fields

$$A_\pm, B_\pm(x, z, t) = \sum_{m=-\infty}^{\infty} A_\pm^m, B_\pm^m(z,t)e^{2\pi i m x/l_x}, \tag{10}$$

each harmonic can be considered as a resonator mode with azimuthal index m. Equations for the wave amplitudes in the quasi-optical approximation can be presented as

$$\left(\frac{\partial}{\partial Z}+\beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_{+}^{m}+\sigma A_{+}^{m}+i\alpha_{2D}(B_{+}^{m}+B_{-}^{m})=J^{m}$$
$$\left(-\frac{\partial}{\partial Z}+\beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)A_{-}^{m}+\sigma A_{-}^{m}+i\alpha_{2D}(B_{+}^{m}+B_{-}^{m})=0 \qquad (11)$$
$$\left(\frac{iC}{2}\frac{\partial^{2}}{\partial Z^{2}}\pm ism+\beta_{gr}^{-1}\frac{\partial}{\partial \tau}\right)B_{\pm}^{m}+\sigma B_{\pm}^{m}+i\alpha_{2D}(A_{+}^{m}+A_{-}^{m})=0$$

Here $J^{m}=\frac{1}{2\pi L_{x}}\int_{0}^{L_{x}}J\exp(-ismX)dX$ is the azimuthal harmonic of the RF current, $s=2\pi/L_{x}$, σ is ohmic losses parameter.

Simulations were carried out for parameters close to those realized in the Strathclyde FEL: lengths of the input, output and regular sections $l_{2D}=10.4$ cm, $l_{1D}=6$ cm, $l_{0}=65$ cm respectively, the gap between conductors was 1 cm and the gain parameter $C\approx 0.007$. For the corrugation depths $a_{2D}=0.05$ cm and $a_{1D}=0.1$ cm the waves coupling coefficients were $\alpha_{2D}=0.5$, $\alpha_{1D}=0.35$.

The field distribution of partial waves in the steady-state regime is depicted in Fig.6 and shows that the main amplification of the forward wave takes place after the input mirror. As a result, the amplitudes of the cut-off modes $B_{\pm}$ excited in the 2D Bragg structure are relatively small. Correspondingly, the ohmic and diffraction losses associated with these modes are also rather small and up to 95% of the RF-energy extracted from the electron beam is radiated by the forward travelling wave A_{+}.

The coaxial FEL based on 2D distributed feedback, which has been developed at the University of Strathclyde, includes an axially symmetric pulsed wiggler with period of 4 cm and pulsed solenoid of length 2.5 m and up to 0.6 T field strength. The FEL was driven by a high-current accelerator which produced a large mean diameter (7 cm) annular electron beam of current 0.5 kA and energy up to 500 keV.

A coaxial 2D Bragg structure was made with the chessboard corrugation on the inner conductor with a period along axis of 8 mm, number of azimuthal variations of 24 and depth of 0.08 mm. "Cold" tests of these structures [5] demonstrated effective 2D Bragg scattering in the vicinity of 37 GHz, which corresponds to the fundamental azimuthally-symmetrical mode ($m=0$) formed from the four waveguide partial waves: forward and backward waves of TEM-type and two counter-rotating whispering-gallery waves of $TE_{24,1}$-type.

In the last stage of the experiment a hybrid resonator consisting of an input 2D Bragg reflector and an output 1D Bragg reflector separated by a regular section was utilized with the parameters described above. The spectrum measurements (Fig.7) demonstrated the establishment of a single-mode oscillation regime including both azimuthal and longitudinal mode control. It is important to note that in accordance with theoretical consideration generation of the fundamental azimuthally-symmetrical mode $m=0$ at the frequency band 37 GHz was observed at any variation of the wiggler field from the zone of self-excitation. The output power was estimated to be about 60 MW.

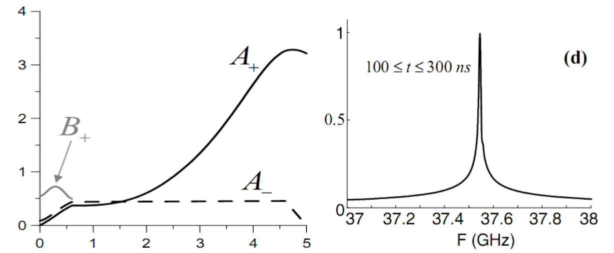

Figure 6: Modelling of coaxial FEL with hybrid Bragg resonator: (a) longitudinal profile of the partial waves in the steady-state regime; (b) output radiation spectrum.

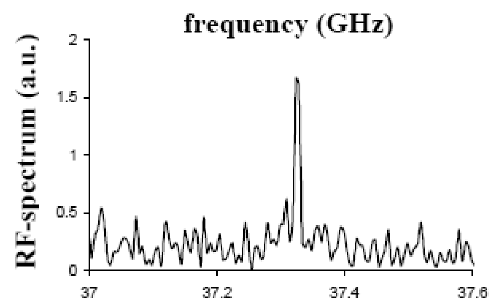

Figure 7: Radiation spectrum of 37-GHz coaxial FEL

CONCLUSION

In this paper we presented the results of theoretical and experimental studies of FELs based on 2D distributed feedback in two different geometries and frequency bands. Modelling of the nonlinear dynamics of the planar and coaxial schemes of the FELs demonstrates the possibility of using 2D distributed feedback for spatial synchronization of radiation from sheet and hollow electron beams having a width and perimeter of up to 10^{2} - 10^{3} wavelengths. Results of the theoretical analysis are corroborated by experimental studies carried out at Budker INP RAS (planar 75 GHz FEL) and Strathclyde University (coaxial 37 GHz FEL). Both experiments demonstrate effective mode control under the oversized parameter of 20 - 25 wavelengths, which is provided by the use of a 2D distributed feedback mechanism. As a result, narrowband radiation of multi-MW power level was achieved.

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