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Progress of the volume FEL (VFEL) experiments in millimeter range ☆

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Abstract

Use of non-one-dimensional distributed feedback in Volume Free Electron Laser gives possibility of frequency tuning in wide range. In present work, dependence of lasing process on the angle between resonant diffraction grating grooves and direction of electron beam velocity is discussed.

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New advances in different areas require the development of tunable, wide-band, high-power sources of coherent electromagnetic radiation in GigaHertz, TeraHertz and higher-frequency ranges. Conventional electron vacuum devices have restricted possibility of frequency tuning (usually it does not exceed 5–10%) for the certain carrier frequency at certain e-beam energy. Volume free electron laser (VFEL) [2,3] was proposed as a new type of free electron laser. Frequency tuning, possibility of use of wide electron beams (several e-beams) and reduction of threshold current density necessary for start of generation, provided by VFEL, make it a basis for development of more compact, high-power and tunable radiation sources then conventional electron vacuum devices could let.

First lasing of VFEL was reported at FEL 2001 [3]. This VFEL operates in wavelength range $\sim$4 mm at electron beam energy up to 10 keV. VFEL resonator is formed by two parallel diffraction gratings with different periods and two smooth sidewalls (see figure in Refs. [3,4]). Interaction of exciting diffraction grating with an electron beam arouses Smith–Purcell radiation. Resonant diffraction grating provides distributed feedback of generated radiation with an electron beam by Bragg dynamical diffraction. Tuning of diffraction conditions is provided by rotation of resonant grating that changes angle between grating grooves and electron beam velocity.

Experimental study of frequency tuning and change of radiation intensity at mechanical

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rotation of resonant diffraction grating is presented in this paper.

General theoretical statements [1,2] should be reminded for better understanding of the experimental results given below. Considering processes in resonator, one should discern the difference between two cases: (a) presence of resonator sidewalls can be neglected; (b) presence of sidewalls of resonator cannot be neglected. For unbounded waveguide (case (a)), two geometries of diffraction are distinguished: those of Bragg and Laue [5]. Laue geometry of diffraction implies that both incident and diffracted waves pass to vacuum through the same boundary of resonator, while at Bragg diffraction, incident and diffracted waves pass through the different boundaries. Absolute instability can appear in Bragg geometry and such system works as generator (for backward Bragg diffraction it converts into a well-known backward-wave tube). For Laue case, convective instability provides only amplification regime.

Generation process in resonator is described by Maxwell equations, containing the space-periodic permittivity of diffraction grating $\chi(\vec{r},\omega) = \sum_{\vec{\tau}\neq 0} \chi_\tau(x)\mathrm{e}^{-\mathrm{i}\tau_y y}\mathrm{e}^{-\mathrm{i}\tau_z z}$, where $\vec{\tau}$ is the reciprocal lattice vector of the diffraction grating [2].

If χ_τ in the above equations is equal to zero, they describe smooth waveguide, which eigenfunctions $|\vec{Y}(x,y)\rangle$ are well known. If presence of waveguide sidewalls cannot be neglected, $(|\vec{Y}_{nm}(x,y)\rangle \sim \sin(\pi n/a)x\sin(\pi m/b)y$, where n, m are the integer numbers, a and b are the transversal dimensions of resonator. Expanding Maxwell equations over eigenfunctions of smooth waveguide $|\vec{Y}_{nm}(x,y)\rangle$, one obtains equations describing generation in continuous effective grating with periodic permittivity $\chi_{\mathrm{eff}}(z)$ [2].

In single-mode approximation, the above problem comes to that of generation (amplification) in one-dimensional periodic medium with effective permittivity:

$$\chi_{\mathrm{eff}}(z) = \chi^{nn(mm)}(z) \sim \int \mathrm{d}x \sin^2\frac{\pi n}{a}x\chi_\tau(x) \times \int \mathrm{d}y \sin^2\frac{\pi m}{b}y\mathrm{e}^{-\mathrm{i}\tau_y y}\mathrm{e}^{-\mathrm{i}\tau_z z}. \quad (1)$$

Presence of diffraction grating in waveguide makes nondiagonal matrix elements $\chi^{nn'(mm')}(z)$, describing transition between modes, different from zero:

$$\chi^{nn'(mm')}(z) \sim \int \mathrm{d}x \sin\frac{\pi n}{a}x\,\chi_\tau(x)\sin\frac{\pi n'}{a}x \times \int \mathrm{d}y \sin\frac{\pi m}{b}y\mathrm{e}^{-\mathrm{i}\tau_y y}\mathrm{e}^{-\mathrm{i}\tau_z z}\sin\frac{\pi m'}{b}y.$$

Presence of sidewalls imparts new feature to diffraction process in resonator, because even in Laue-like case (which corresponds to Laue geometry of diffraction if neglecting the sidewalls) the matrix element $\chi_{\mathrm{eff}}(z)$ differs from zero. And, as a result, generation regime can be reached at Laue-like geometry, in contrast with an unbounded waveguide, where Laue geometry provides only amplification regime, while generation is possible at Bragg diffraction.

General view of microwave signal is presented in Fig. 1a. Presence of several microwave peaks is the manifestation of longitudinal cavity modes. Frequency difference $\Delta\nu$ associated with the change ΔE of electron energy E ($\nu \sim \sqrt{E(\mathrm{keV})}$) can be estimated as $\Delta\nu = \nu_0\Delta E/2E_0$. According to measurements $\nu_0 \approx 54$ GHz, $\Delta E \approx 0.13$ keV for two next distinguished peaks (Fig. 1b.), hence, frequency difference for them can be estimated as $\Delta\nu \sim 0.57$ GHz.

Now let us consider behavior of lasing efficiency with grating rotation. Rotation of diffraction grating changes components of reciprocal lattice vector. From Eq. (1) it is easy to see that $\chi_{\mathrm{eff}}(z)$ decreases with τ_y growth. Change of $\chi_{\mathrm{eff}}(z)$ yields change of generation conditions and, in particular, generation threshold. Reduction of $\chi_{\mathrm{eff}}(z)$ results in decrease of generation efficiency (Fig. 2). But, interaction efficiency can be increased if recollect that at certain value of current density, the intensity is proportional to the term $\mathrm{e}^{-(4\pi/\lambda\beta\gamma)h}$ [6] where h is the distance from electron to the grating, γ is the Lorentz factor, λ is the radiation wavelength, $\beta = v/c = \sqrt{2E(\mathrm{keV})/511}$. As a result, energy of electron beam at certain current density should be increased (to increase factor $\mathrm{e}^{(-4\pi/\lambda\beta\gamma)h}$) to overcome decrease of χ_{eff}.

Non-one-dimensional feedback, being used in VFEL, provides tuning of radiation frequency by diffraction grating rotation. Measured frequencies

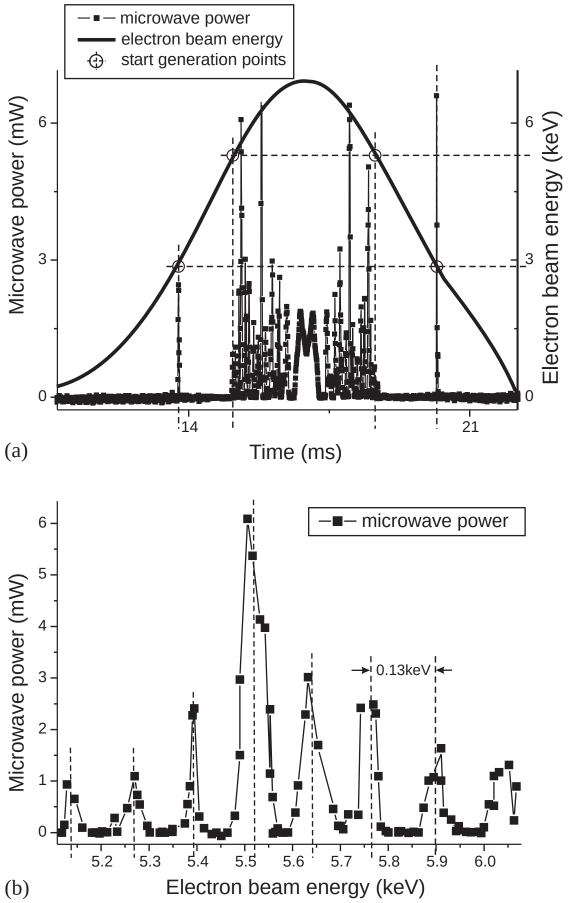

Fig. 1. (a) General view of microwave signal. (b) Dependence of microwave power on electron beam energy.

at rotation of resonant diffraction grating for microwave peak, corresponding electron beam energy 2.9 keV are shown in Fig. 3. Measured frequency change well according to the theoretical predictions [1,2].

VFEL generator can be considered as a new type of tunable backward wave tube with variable period (due to gratings rotation) and VFEL amplifier is a new type of tunable travelling wave tube.

Frequency tuning, possibility of use of wide electron beams (several e-beams) and reduction of threshold current density necessary for start of generation, provided by VFEL, make it a basis for development of more compact, high-power and

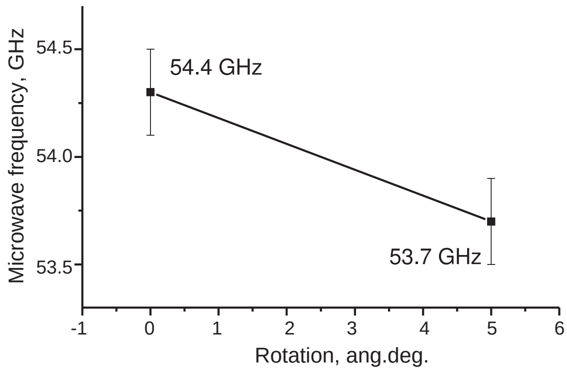

Fig. 3. Measured frequencies at rotation of resonant diffraction grating.

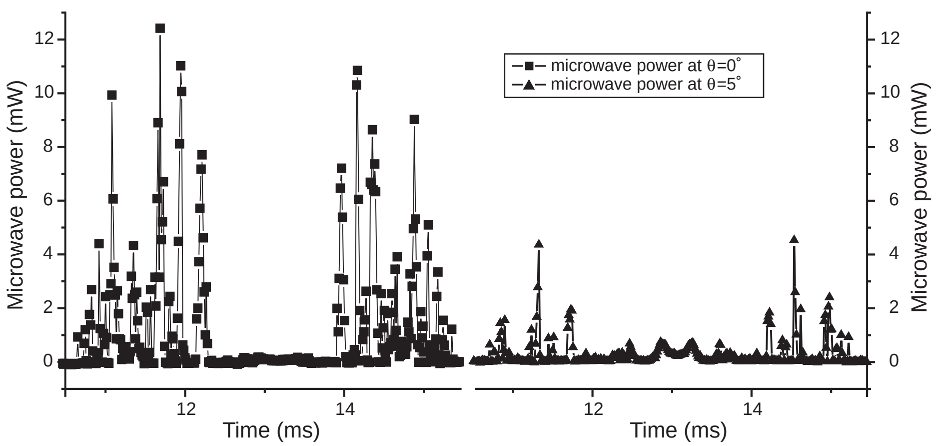

Fig. 2. Change of lasing efficiency with grating rotation, θ is the angle of grating rotation, $\theta = 0$ when grating grooves are perpendicular to e-beam velocity.

tunable radiation sources then conventional electron vacuum devices could let.

New VFELs with electron beam energy up to 30 and 500 keV have been developed for next set of experiments.

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