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Experimental observation of radiation frequency tuning in "OLSE-10" prototype of volume free electron laser

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Abstract

Feasibility of the conception of the volume free electron laser was verified by "OLSE-10" experimental prototype. Measurements of key parameters of the microwave radiation of the prototype have confirmed the features predicted theoretically. Possibility of smooth tuning of the radiation frequency and decrease of the threshold current density in a volume free electron laser are demonstrated. The set of VFEL characteristics showed that it might be the prospective source of tuneable polarized radiation in the microwave and Terahertz ranges [V.G. Baryshevsky, K.G. Batrakov, A.A. Gurinovich, et al., Nucl. Instr. and Meth. A 507 (2003) 137; V.G. Baryshevsky, A.A. Gurinovich, LANL e-print archive: physics/0409107; V.G. Baryshevsky et al., LANL e-print archive: physics/0409125]. Application of radiation of these wavelength ranges in science and engineering is highly challenging.

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Keywords: Volume free electron laser (VFEL); Volume distributed feedback (VDFB); Diffraction grating; Smith–Purcell radiation

1. Introduction

Conventional vacuum electronic devices, either amplifiers or generators, provide tuning of radiation frequency mainly due to change of the electron beam energy and have slight possibility of frequency tuning at fixed energy of the electron beam [1–4]. This is a strong intrinsic restriction of devices with one-dimensional distributed feedback. The output power of these systems is also rigidly limited.

Volume (non-one-dimensional) distributed feedback [5] eliminates the above shortcoming and makes available some new features:

1. frequency tuning at a fixed energy of the electron beam in the significantly wider range than conventional systems can provide;
2. more effective interaction of the electron beam with an electromagnetic wave that allows to reduce the threshold electron beam current;
3. reduction of limits for the available output power by the use of wide electron beams and diffraction gratings of large volumes;
4. simultaneous generation at several frequencies.

Mechanism of engendering of volume distributed feedback in vacuum electronic devices was proposed in [5,6] for the new type of FEL, which was called "volume free electron laser" (VFEL) [7–9].

Experiments with the VFEL prototype named "OLSE-10"[1] demonstrated for the first time smooth tuning of the radiation frequency in the wavelength range 4–6 mm

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[1] "OLSE" is the abbreviation of the russian analogue of the term "volume free electron laser" and "10" (keV) indicates the highest electron beam energy available in the experiment.

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[7,10] and decrease of the threshold current density in the volume free electron laser.

2. Experimental facility

The general schematic of VFEL operation is shown in Fig. 1. The electron gun of "OLSE-10" produced the ribbon-like electron beam with the energy ~10 keV. This beam had cross-section $\sim 10 \times 2\ \mathrm{mm}^2$ and was guided by magnetic field ~3 kG through a resonator formed by two diffraction gratings and lateral walls T-shaped in cross-section. Diffraction gratings had length 100 mm and different periods $d_1 = 0.67$ mm and $d_2 = 3.00$ mm. They were made of silver-plated brass with fluting steps of grooves rectangular in cross-section. The electron beam was guided as close as possible to the grating with the smaller period to induce Smith–Purcell radiation. Period of this grating had been chosen to make a harmonic of an electromagnetic wave be in synchronism with the electron beam. The distributed feedback was provided mainly by the second grating that effectively reflects only waves with wavelengths satisfying the Bragg condition.

Machinery of the "OLSE-10" resonator allowed to vary the distance between gratings, distance between lateral walls and to rotate the diffraction gratings (i.e. to change the angle between the grating grooves and the electron beam velocity) in the range ±7°.

The distance between gratings, which is important to be controlled, was determined by measurements of the electric capacity of the variable capacitor formed by the diffraction gratings.

Microwave radiation of the VFEL passed from a vacuum chamber to atmosphere through a window made of fused silica and was detected by a microwave diode detector head with a waveguide input mounted on a receiving horn antenna. During experiments the following parameters were measured: the power of microwave pulses, the electron beam energy (the electron gun high voltage) and total current, currents through the Smith–Purcell grating and in the anode circuit. The value of the current through the Smith–Purcell grating indicated how close the beam was going above this grating.

To chose optimal experimental parameters the electromagnetic properties of resonator were studied by electrodynamic modelling without an electron beam. In particular, the distance between the gratings, which determined radiation transverse modes, might be installed only during preliminary positioning outside of the vacuum chamber prior the system assembling. As it was difficult to calculate the optimum distance between the gratings, then electrodynamic modelling experiments were performed with the external microwave source at the dedicated test bench to obtain the resonator transparency patterns.

The test bench for electrodynamic modelling consisted of a microwave generator (operation range ~ 4 mm), a microwave power meter, and a holder, which provided positioning of the "OLSE-10" resonator and its connection to the detector of the power meter at necessary angle relative to the output waveguide of the generator with the accuracy ±0.5°. Plasticine scatterer was positioned on the generator output to provide a wave from the generator to be quasi-plane on the distance $\geqslant 10\lambda$. The plane wave was directed into the resonator falling onto the feedback grating with period d_2 under the angle, which corresponded the emission angle of Smith–Purcell radiation with the wavelength ~4 mm from electrons with the energy ~10 keV passing near the grating with the period d_1. The emission angle is denoted by Θ in Fig. 1 and was about 40–45° in the experiments. Then the distance between the gratings was changed and the power of transmitted microwave radiation was recorded (Fig. 2).

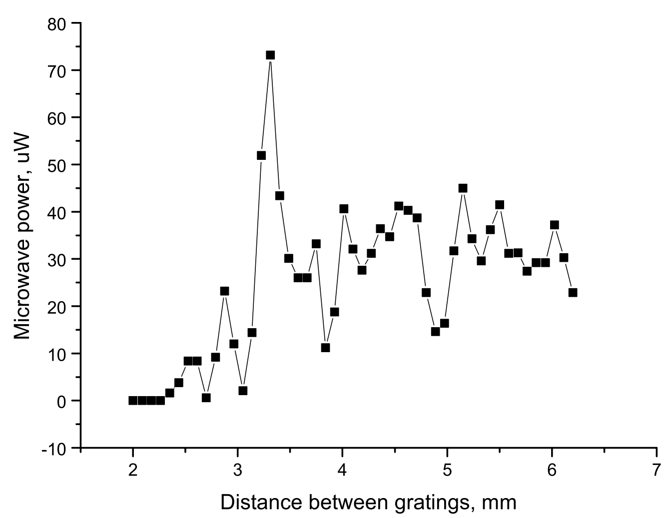

Fig. 2. The transparency pattern of the "OLSE-10" resonator, as in laboratory modelling.

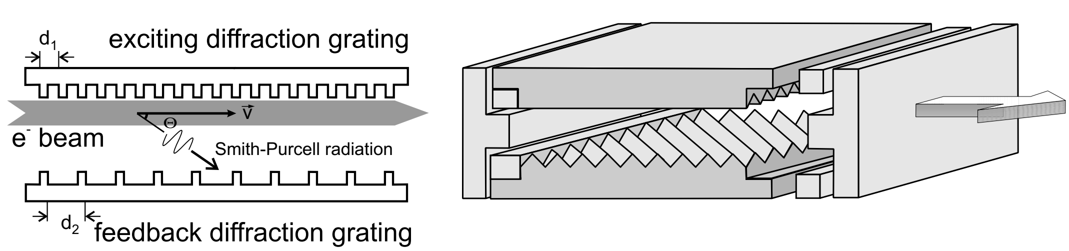

Fig. 1. Outline of the VFEL prototype operation.

Using the results of preliminary electrodynamic modelling we set the initial distance between gratings that was weakly adjusted during the experiments to provide the best positioning of the Smith–Purcell grating with respect to the electron beam. The electron beam position was monitored by burning-through targets made of the polyester fibres. Alignment of the resonator, as a whole, relative to the electron beam was performed using special gearing, which provided cross motion and retention of the resonator in the laser channel with the help of micro-screws. The distance between gratings was finely tuned by moving the Smith–Purcell grating.

3. Experimental results

The experimental technique was based on search of OLSE-10 generation conditions by electron beam energy sweeping from zero up to the certain maximal energy (<10 keV). Such technique provided to observe radiation generation for several electron beam energies, for which resonant conditions were fulfilled. The oscillograms of the microwave signal looked like a set of pulses due to satisfaction of generation conditions some times during energy sweep. Superimposing of oscillograms for the microwave signal and those for high voltage of the electron gun provided to correlate microwave pulse with the certain electron energy. The lasing threshold current was determined by electron gun current gradual decrease in series of iterative laser starts. The microwave signal detected by the detector diode V_{mw} and the voltage of the high-voltage generator, equivalent to the beam energy E(keV) (the sample oscillograms are given in Fig. 3) were recorded to appropriate files together with the results of measurement of the electron gun anode current I_{a}, total current of the system I_{t}, and current running through the Smith–Purcell grating I_{g}.

The output microwave signal was normalized to the effective current I_{eff} that was defined as follows. The beam current was equal to the difference between the total current and the current measured on the anode. Suppose that the beam had the Gauss distribution in the cross-section, the transversal distribution of the beam current could be expressed as:

$$\frac{I_{\mathrm{t}} - I_{\mathrm{a}}}{\sqrt{\pi}\sigma} \exp\left[-\frac{(x-x_0)^2}{\sigma^2}\right], \tag{1}$$

where I_{t} is the total current in the system, I_{a} is the current measured on the anode, σ is the constant describing the Gauss distribution, x_0 is the position of the electron beam axis. As the beam had to be guided as close as possible to the Smith–Purcell grating, a part of beam electrons was absorbed producing the grating current I_{g}. Integrating (1) over $[0;-\infty]$, we obtained the current running down the Smith–Purcell grating:

$$I_{\mathrm{g}} = \frac{I_{\mathrm{t}} - I_{\mathrm{a}}}{2}\left(1 - \mathrm{erf}\left[\frac{x_0}{\sigma}\right]\right), \tag{2}$$

where $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(-x^2)\,\mathrm{d}x$ is the error function. Thus, the effective beam current that considered only those electrons, which effectively interacted with the decelerated wave, was evaluated as

$$I_{\mathrm{eff}} = \frac{1}{2}(I_{\mathrm{t}} - I_{\mathrm{a}})\left(\mathrm{erf}\left[\frac{w - x_0}{\sigma}\right] + \mathrm{erf}\left[\frac{x_0}{\sigma}\right]\right), \tag{3}$$

where w is the distance of effective interaction defined as

$$w = \frac{\lambda}{4\pi}\sqrt{\frac{2E}{mc^2}} = \frac{30}{4\pi v}\sqrt{\frac{2E}{511}}. \tag{4}$$

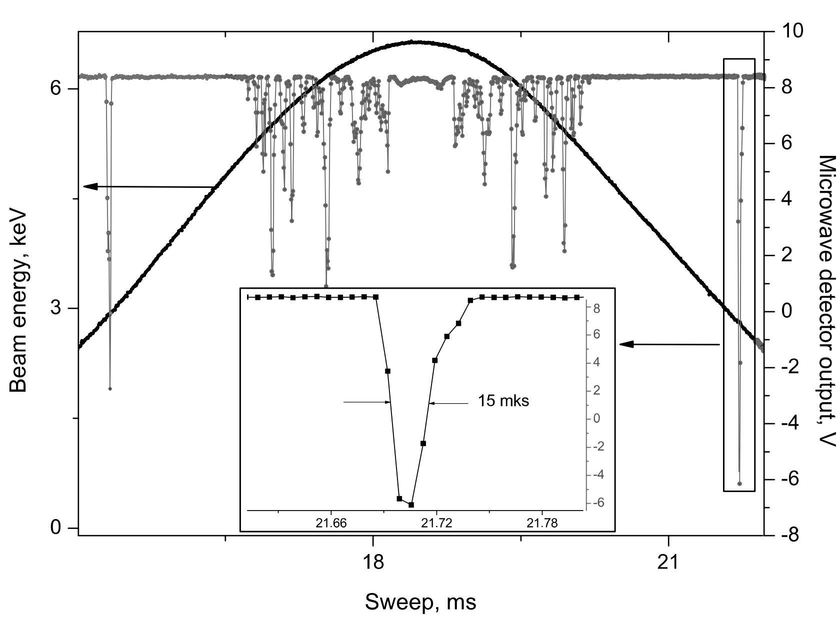

Fig. 3. The typical view of "OLSE-10" signals.

Then the final practical expression for the effective current including only measurable values was obtained:

$$I_{\text{eff}} = \frac{I_{\text{t}} - I_{\text{a}}}{\sqrt{\pi}} \exp(-y^2) \frac{1.5}{\sigma(\text{FWHM})} \frac{\sqrt{E(\text{keV})}}{v(\text{GHz})} \times \left(1 + y \frac{1.5}{\sigma(\text{FWHM})} \frac{\sqrt{E(\text{keV})}}{v(\text{GHz})}\right), \quad (5)$$

$$\text{erf}(y) = 1 - \frac{2I_{\text{g}}}{I_{\text{t}} - I_{\text{a}}}.$$

The beam cross size σ(FWHM) was determined using its print at the polyester fibre target and accepted as equal to 2.0 mm for further calculations. Then the output signal was normalized on number of electrons went on distance w from the Smith–Purcell grating, which provided effective interaction of the beam with the decelerated wave. It should be noted that high voltage stability necessary for VFEL operation can be obtained from comparison of the width of generation lines with the ranges of the respective change of the electron beam energy. "OLSE-10" lasing was observed in energy range $\sim \pm 1\%$ relative to the exact synchronism condition.

Microwaves were detected by the diode detecting head, calibrated with the help of the microwave generator, power meter and digital voltmeter. Calibration data were recorded to curves, which were used to convert the detector signals from the voltage scale (Fig. 3, insert) to the power scale (Fig. 4) by means of an interpolation program. Then signals were processed by a standard set of procedures: smoothing, baseline subtraction, and identification of peaks.

One of the main attractive VFEL features is the opportunity of rather simple tuning of the output signal frequency due to rotation of gratings. Since the VFEL signal was observed as periodic pulses of microsecond duration in millimeter wavelength range, then to measure the laser pulse carrier frequency we chose a quasi-optic technique frequently used in the millimeter wavelength range. The radiation frequency (wavelength) can be obtained by measuring of the reflection factor of an electromagnetic wave from a dielectric plate with the certain dielectric permittivity and thickness $\sim \lambda\sqrt{\varepsilon'}$, where ε' is the real part of the dielectric permittivity, λ is the wavelength in vacuum. In spite of the formal simplicity of this method, the issue of its application is the realization of particular conditions, i.e. modelling of a plane wave, minimization of diffraction losses, providing microwave power total collection, etc. To realize this approach an experimental set-up was developed on the base of broadband hollow dielectric beam-guides. The set of plates of microwave ceramics 22XC with the thickness from 0.5 mm to 2.0 mm with 0.5 mm step were used as dispersive elements. Combining these plates we selected the best measurement conditions and thus achieved the best accuracy of evaluation of the pulse carrier frequency. Simultaneous measurement of the transmitted and reflected signals allowed evaluating of the carrier frequency of each single pulse of the laser. The technique of "OLSE-10" frequency measurements is published in [11] in more detail.

The spectrum of radiation generated by the Smith–Purcell grating in our case is described by the practical formula

$$v(\text{GHz}) \cong \frac{19 \cdot \cos\varphi}{d(\text{mm})(1 - 0.06\sqrt{E(\text{keV})}\cos\theta)} \sqrt{E(\text{keV})}, \quad (6)$$

where d is the distance between grating grooves, E is the electron beam energy, φ is the angle between direction of electron beam velocity and reciprocal lattice vector of the grating, and θ is the angle between direction of a photon radiation and the electron beam velocity. Changing the angle between the feedback diffraction grating and electron beam velocity made possible to observe smooth tuning of the radiation frequency.

To demonstrate tuning of VFEL frequency the dedicated experiments were carried out (Fig. 5). It should be

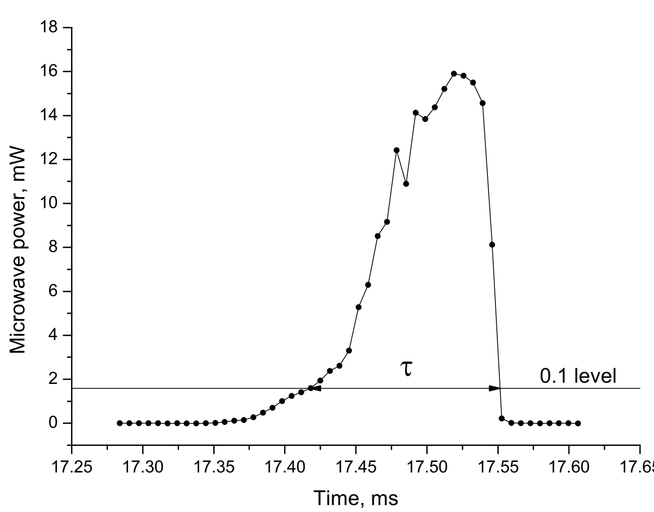

Fig. 4. The microwave pulse corresponding to 2.9 keV beam energy transferred to a power scale, τ is the duration of a signal at 0.1 level.

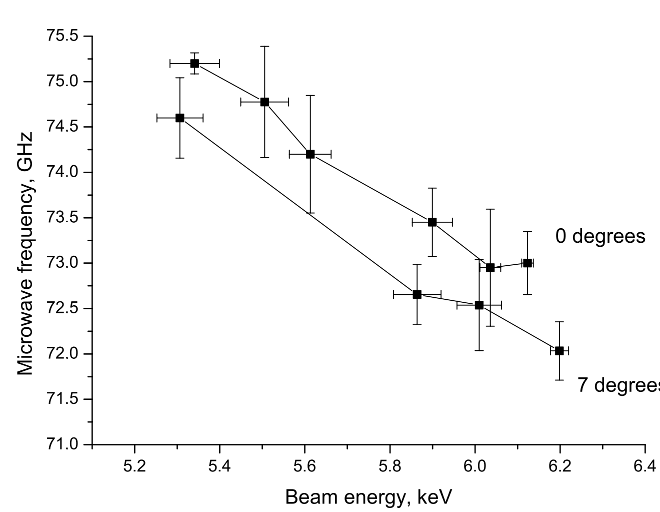

Fig. 5. The measured carrier frequencies of pulses corresponding to 5.3–6.2 keV beam energy for two positions of feedback grating.

noted, that due to change of radiation emission conditions at grating rotation, the radiation spectra were different for different grating positions. And even some of peaks (modes) of the signal disappeared after the grating rotation (compare the top and bottom dependencies in Fig. 5). Horizontal error bars in Fig. 5 correspond to dispersion of the electron beam energy, which is about ±1%.

The laser radiation polarization was studied by measuring its power while rotating the horn antenna with the microwave detector around the axis connecting centers of the laser resonator and the detector. Results of measurements for microwave peaks corresponding to 2.9 keV beam energy are presented in Fig. 6(a), curve 1. As the hand-made antenna had the specific directional diagram, it was investigated in preliminary laboratory modelling. First, the polarization of radiation provided by the test generator was studied with the help of the detector with a waveguide input. The obtained dependence is shown in Fig. 6(b) (curve denoted "waveguide") and it is well described by $\cos^2\varphi$ function that is typical for an optical system consisting of the crossed identical polarizer and analyzer. Then the polarization characteristic of radiation provided by the test generator was recorded using the detector with the antenna (see Fig. 6(b) (curve "antenna")). It appeared to be a curve of complex shape with a maximum displaced relative to the case of symmetric location of generator and detector, corresponding to 90° in Fig. 6(a) and (b). At last, the polarization pattern of the test generator radiation transmitted through the "OLSE-10" resonator model was recorded by the detector with the open waveguide input (Fig. 6(a), curve 3). After the subtraction of the antenna instrument response from the measured "OLSE-10" microwave signal, the curve 2 in Fig. 6(a) (after subtraction) appeared practically coinciding with the curve 3 (obtained for the signal from the test generator). Thus, it was possible to conclude that polarization characteristic of VFEL radiation basically was determined by the laser cavity resonator structure. In our case radiation was polarized strongly than radiation from the waveguide output of the TWT-based test generator and, besides, the polarization plane was turned 40–45 angular degrees relative to the plane of the system symmetry. This is due to the chosen experiment geometry ($\Theta = 40$–$45°$, see Fig. 1).

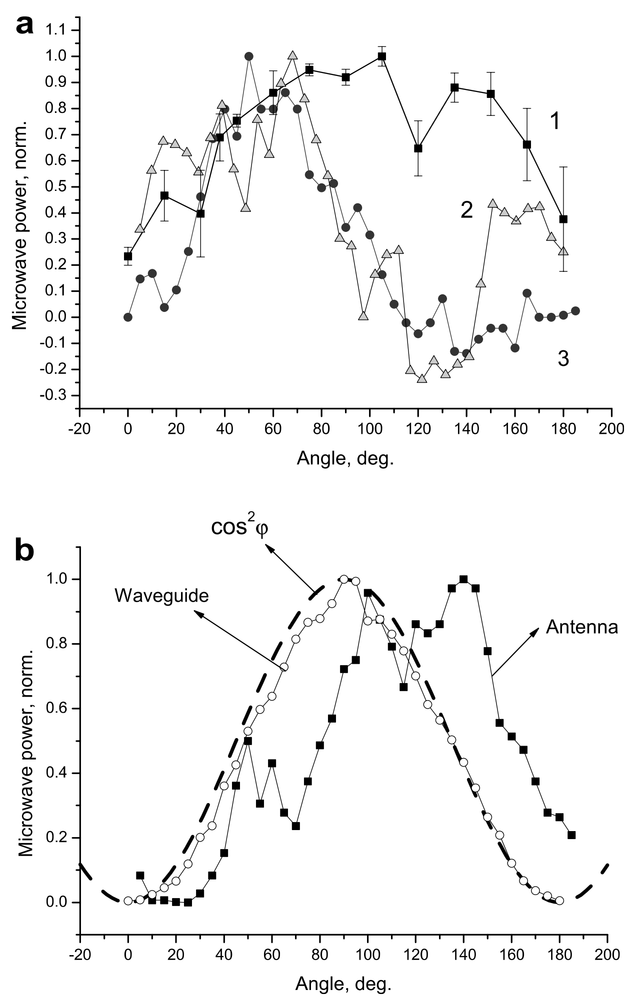

Fig. 6. (a) – curve 1 is the normalized power of "OLSE-10" radiation as a function of the angle of detector rotation around the system symmetry axis; curve 2 is the difference of the curve 1 and the detector instrumental response; curve 3 is the normalized power of the test generator radiation transmitted through the resonator model as a function of the angle of detector rotation; (b) – the instrumental response functions of the microwave detector without the antenna ("waveguide") and with it.

To find out "OLSE-10" lasing threshold conditions as well as to obtain the dependence of its total microwave power on the effective current, the series of measurements were performed for microwave peaks corresponding to 2.9 keV beam energy (results are presented in Fig. 7). Here the pulse power P_p was determined as

$$P_p = \frac{1}{\tau}\int_0^{\tau} p(t)\,dt, \tag{7}$$

where $p(t)$ corresponds to the power signal above 0.1 level and τ is the duration of the signal above 0.1 level as it is shown in Fig. 4. The pulse values of the total current I_t

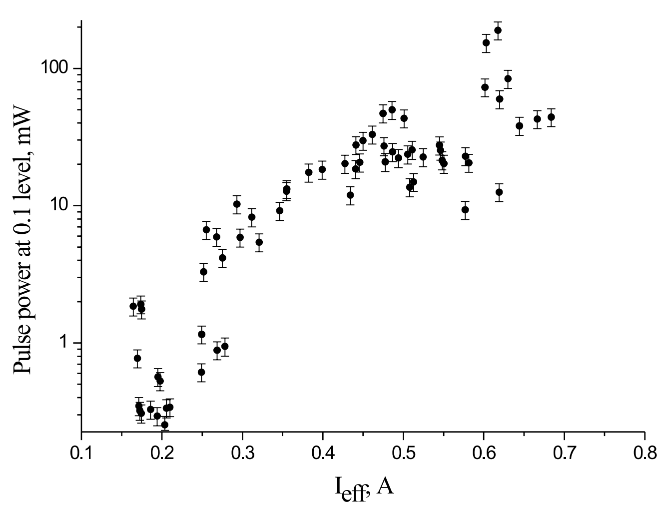

Fig. 7. Dependence of the microwave pulse power on the effective current at 2.9 keV beam energy.

and grating current I_g, which are required for I_{eff} determination on formula (5), were calculated in the same way.

Due to instability of "OLSE-10" operation at the high effective currents, it was difficult to define exactly the functional behavior of the radiation power dependence on the electron beam current. As it was neither quadratic nor linear, it was possible only to state that partly coherent mode of the radiation was observed and this issue required further research.

Technological ports of various dedications in the laser drift tunnel occupied approximately 10% of its area. The output quartz window (its permittivity at 54 GHz is 3.8) was of 4.5 mm thickness. Its transmittance factor was 0.9 and the ratio of the areas of the output window and antenna was 0.25. Totally the factor of radiation transfer from the laser resonator output to the detector without taking into account absorption in air could be estimated as $\sim$0.2. The maximal measured by the detector pulse power was about 170 mW that gave radiation power directly at the output of the resonator of about 850 mW. Taking into account that the effective current was $\sim$600 mA and the electron beam energy was 2.9 keV, the achieved efficiency of the beam power to the radiation power transformation can be estimated as 0.05%.

4. Conclusion

Feasibility of the conception of the volume free electron laser was verified by "OLSE-10" experimental prototype. Measurements of key parameters of the microwave radiation of the prototype have confirmed the features predicted theoretically. The set of VFEL characteristics showed that it might be the prospective source of tuneable polarized radiation in the microwave and Terahertz ranges [8,12,13]. Application of radiation of these wavelength ranges in science and engineering is highly challenging.

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