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First lasing of a volume FEL (VFEL) at a wavelength range $\lambda \sim$ 4–6 mm☆

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Abstract

First lasing of a volume free electron laser in the millimeter wavelength range is observed.

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The most essential feature of FEL-based generators, likewise all other types of generators, is a positive feedback, which is formed by a system of mirrors, or distributed feedback based on the diffraction in spatially periodic medium, when wave vectors of transmitted and reflected waves are colinear (one-dimensional feedback). The distinction of a volume FEL (VFEL) is a volume (non-one-dimensional) multi-wave distributed feedback (VDFB). VDFB performs two basic functions simultaneously:

(1) it provides more effective interaction of an electromagnetic wave with an electron beam due to a new dispersion law;
(2) it forms a volume distributed mirror retaining radiation in the interaction region.

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It is well-known that each radiative system is defined by its eigenmodes and by the so-called dispersion equation, which in the case of small perturbations (linear regime) describes possible types of waves in the system and the relation between frequency and wave number of the system's eigenmodes. Thorough analysis of the FEL dispersion equation [1] shows that:

1. the dispersion equation for FEL in the collective regime coincides with that for a conventional travelling wave tube amplifier (TWTA) [2];
2. the FEL gain (increment of electron beam instability) is proportional to $\rho^{1/3}$ (likewise TWTA), where ρ is the electron beam density.

But the law of instability of the electron beam can be essentially changed by passing through a spatially periodic medium. This fact was indicated for the first time in Ref. [3]. There dispersion

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equations are obtained and investigated for conditions of multi-wave diffraction. It is shown that the new law of electron beam instability arises in the points of diffraction roots degeneration. The amplification of the electromagnetic wave and the generation gain are sharply changed in these points. In Ref. [3] it is shown that the increment of instability in these points is proportional to $\rho^{1/(3+s)}$, here s is the number of surplus waves appearing due to diffraction (for example, in case of two-wave Bragg diffraction $s=1$, for three-wave diffraction $s=2$ and so on). This increment differs from the relevant increment for a one-wave system which is proportional to $\rho^{1/3}$. This result is also valid for an electron beam which moves in the vacuum close to the surface of spacially periodic medium [4] (or in a vacuum slit made inside a periodic medium). Explicit expressions for the dependence of generation starting current j on interaction length L are obtained in degeneration points [5]: $j_{\text{start}} \sim 1/\{(kL)^3(k\chi_\tau L)^{2s}\}$. The advantages of VFEL are exhibited in a wide spectral range from microwaves to X-rays [5–8]. Experimental modelling of electrodynamic processes in the volume diffraction grating for the millimeter wavelength range [8] confirms the possibility to obtain extremely high Q-factor for a system with two strongly coupled waves.

First lasing of the VFEL in the millimeter wavelength range is reported in the present work. Two diffraction gratings with different spatial periods are used to form a volume resonator. It should be noted that the generation in non-relativistic TWT devices under similar conditions is impossible at a single harmonic, since the wavelength of the emitted radiation considerably exceeds the period of the TWT spiral (or corrugation period). Lasing of the considered VFEL type was described for the first time in Ref. [9], where the theoretical model of its operation was presented.

In the considered setup the VFEL resonator is formed by two diffraction gratings with different periods and two smooth side walls, the grooves of diffraction grating are oriented at the non-zero angle with respect to the direction of electron beam velocity. The cross-section of the resonator is rectangular and constant along all its length. But the distance between diffraction gratings can be varied in different experiments. A detailed block-scheme of the experimental setup and construction of resonator are considered in Ref. [10]. The interaction of the first diffraction grating (exciting grating) with the electron beam causes the generation of Smith–Purcell radiation. The second (resonant) grating establishes the distributed feedback of the generated radiation with the electron beam by Bragg dynamical diffraction [11], it can rotate to provide the tuning of the conditions of two-wave diffraction. The length of the resonator is 100 mm, periods of the exciting diffraction grating and resonant diffraction grating are 0.67 and 3 mm, respectively. The distance between the grooved surface of the exciting grating and the electron beam can be varied during the experiment that allows to increase the efficiency of the generation process.

The ribbon e^--beam with a profile of 10 mm × 1 mm emitted by the thermal cathode (tungsten labilized by barium or calcium iridate) is formed in a Pierce gun without beam compression. The electron beam is guided in the VFEL resonator by the magnetic field ~3 kG. Electrons are emitted in the pulsed regime (unipolar pulse with sinusoidal shape and pulse duration ~10 ms) in sequence of two or three voltage pulses (voltage amplitude can vary from 1 to 10 kV). The generated radiation is outcoupled by a radio-transparent window (plexiglas) to the microwave diode coupled with a horn.

The generation of the microwave radiation ($\lambda \sim$ 4–6 mm) with a pulse power of ~3–4 W was detected at an electron energy ⩾5 keV. The oscillogram of the VFEL lasing is shown in Fig. 1.

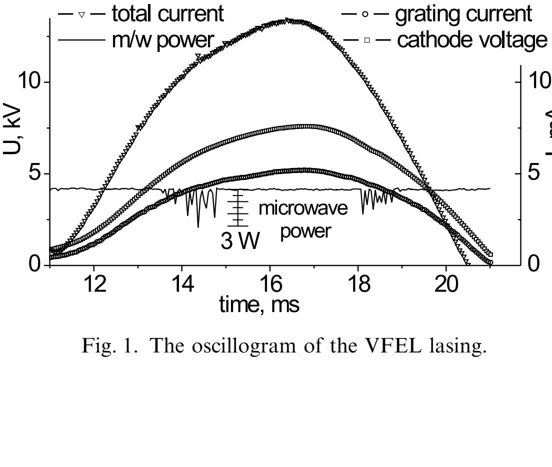

Fig. 1. The oscillogram of the VFEL lasing.

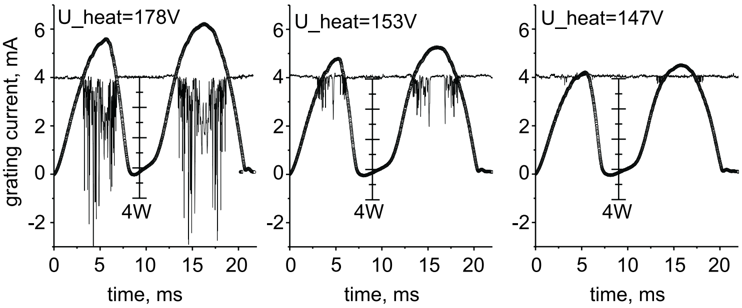

Fig. 2. Threshold conditions of the VFEL lasing (more details see in Ref. [10]).

Evaluating the real efficiency of lasing we should take into account that only parts of electron beam interact with the electromagnetic wave effectively. The cross-section of this part can be estimated as $\delta \sim \lambda u/4\pi c < 0.1$ mm (i.e. $<10\%$ of the total cross-section of the electron beam). To control the efficiency of interaction of the electron beam with the diffraction grating the value of the grating current (i.e. part of total electron beam current falling to the grating) was monitored. The continuous generation of radiation was observed at grating currents > 35 mA. To define threshold conditions the beam current was changed by varying the cathode heating voltage. The dependence of the power of emitted microwave radiation on the cathode heating voltage and grating current (Fig. 2 and [10]) illustrates threshold conditions of generation. It is clear from Fig. 2 that the reduction of the current leads to a decrease of the radiation power. The peaks on radiation power curve gather near an electron beam energy ~ 5 keV when the grating current tends to the threshold value ~ 35 mA. The lasing starts at voltage value ~ 5 kV, which is determined by the diffraction grating period. At the electron beam energy ~ 5 keV the mode with the highest Q-factor is excited. For this reason, when the grating current tends to the threshold value, the region of generation tends to a narrow band near to 5 kV. At higher current values the radiation appears in an electron energy range 5–7.5 keV that demonstrates the excitation of the other modes with smaller Q-factors, for which the working current exceeds the starting that.

First lasing of volume FEL was observed and the experimental results completely confirmed the theoretical predictions [3–7].

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