VOLUME FREE ELECTRON LASER WITH A "GRID" PHOTONIC CRYSTAL WITH VARIABLE PERIOD: THEORY AND EXPERIMENT

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Abstract

Volume Free Electron Laser with a photonic crystal (crystal-like artificial periodic structure) formed by metallic threads periodically strained inside a cylindrical waveguide is studied. Theoretical analysis of operation of Volume Free Electron Laser using a "grid" photonic crystal with variable period is accompanied by the discussion of experimental results. Radiation spectra for different configurations of the photonic crystal are considered.

INTRODUCTION

Volume Free Electron Laser (VFEL) is a peculiar kind of radiation generators using volume multi-wave distributed feedback [1, 2, 3, 4].

One of the VFEL types uses a "grid" photonic crystal formed by periodically strained threads either dielectric [5] or metallic ones [6, 7, 8, 9] as a volume resonator.

Theoretical analysis [6, 8] and experimental studies [7, 9] show that a periodic metal grid does not absorb electromagnetic radiation and the "grid" photonic crystal, made of metal threads, is almost transparent to electromagnetic waves within the frequency range from GHz to THz.

This is confirmed in the experiments with the photonic crystal built inside a rectangular cross-section waveguide. The "grid" structure is made of separate frames each containing a layer of 1, 3 or 5 parallel threads joined so that they form a "grid" structure enabling to produce the radiation with the frequency $\sim$ 8.4 GHz for 100 keV electrons. In the experiments [7, 9] the generation in the "grid" VFEL is observed in BWO regime. The dependence of the lasing intensity on the photonic crystal length is obtained: for the crystal with more than 14 periods ($\sim 3 \cdot \lambda$) saturation is reached.

The theory of VFEL with a spatially variable period is developed in [11, 12, 13]. The "grid" structures of two different periods built inside a rectangular cross-section waveguide form a photonic crystal with a variable period. The smaller period of a photonic crystal is chosen to provide the same radiation frequency for the electron beam, which has lost a part of its energy for radiation in the section with the longer period. Two radiation peaks with the frequency close to 8.4 GHz for both of them are apparent in these experiments. Their intensities are also comparable and, as a result, the detected output is almost twice as high as that for the experiments with "grid" photonic crystal with a fixed period. Experimental results confirm the conclusion that a photonic crystal with a variable period could increase VFEL radiation output.

The main disadvantage of VFEL with resonators of rectangular cross-section is the presence of additional perturbations of the electron beam. While the axially-symmetrical electron beam is guided through the rectangular waveguide by an external magnetic field, the presence of waveguide edges causes additional electromagnetic forces. These electromagnetic forces sufficiently influence the trajectories of electrons and may bring out the spike oscillation in radiation process, which is crucial for lasing within the millimeter wavelength range. The most effective way to avoid such a problem is application of a circular cross-section waveguide with fine surface treatment.

In the present paper Volume Free Electron Laser with a photonic crystal (crystal-like artificial periodic structure) formed by metallic threads periodically strained inside a cylindrical waveguide is studied. Theoretical analysis of operation of Volume Free Electron Laser using a "grid" photonic crystal with a variable period is accompanied by discussion of the experimental results. Radiation spectra for different configurations of the photonic crystal are considered.

DESIGN OF THE VFEL WITH VARIABLE PERIOD

Two "grid" photonic crystals are built up from tungsten threads of 100 μm diameter inside a circular waveguide with the internal diameter $D = 50$ mm. Each crystal has 12 periodically arranged layers with the periods $d_1 = 12.5$ mm and $d_2 = 10.5$ mm. A layer has 7 threads 6 mm distant from each other (see Fig.1).

The resonator of 300 mm length is formed by different assemblies of photonic crystals with the certain period (Fig.2). A pencil-like electron beam with the maximum electron energy 250 keV is guided through the resonator by the magnetic field ~ 1.6 tesla. The electron beam current is about 2 kA.

SIMULATION OF VFEL RESONATOR

The electromagnetic field structure is simulated for a single period of a photonic crystal with periodic boundary conditions and defined phase shift. E-field structure for TM_{01} is shown in Fig.3.

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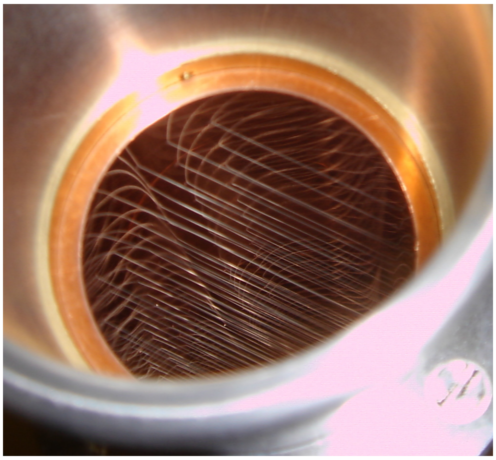

Figure 1: VFEL resonator design (inside view)

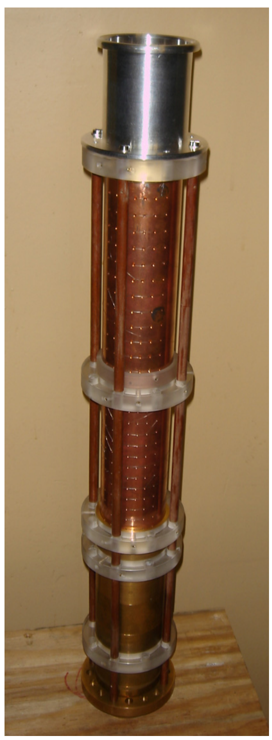

Figure 2: VFEL resonator design

The dispersion diagrams numerically calculated for TM_{01} mode are shown in Fig.4 by solid curves. Dashed lines correspond to the different electron energies.

RESULTS OF THE EXPERIMENT

Two types of experiments are carried out:

- Radiation from each of two photonic crystals with the certain period is analyzed;
- Radiation from the photonic crystals with a variable period, which are assembled from two photonic crystals with the certain period in different sequence is studied.

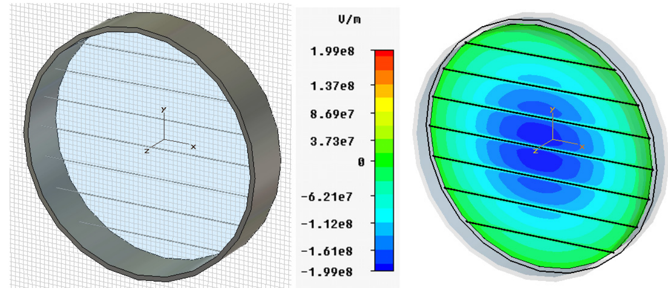

Figure 3: Electric field structure in VFEL resonator

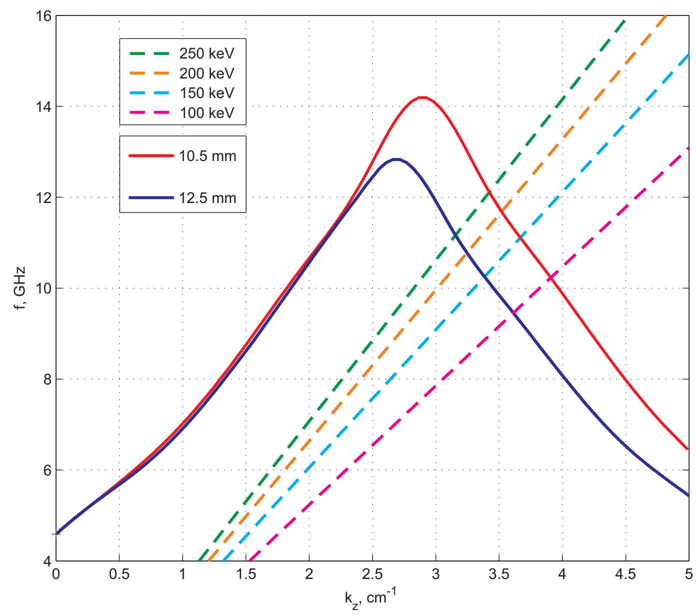

Figure 4: The dispersion diagrams for TM_{01} mode

The goal of the experiments is to observe the correlation between the radiation pulse duration and current (voltage) pulse and to compare spectra and pulse form for different photonic crystals. According to the simulation (see Fig.4) the radiation from the photonic crystal with $d_1 = 12.5$ mm has the frequency from 9.0 to 11.0 GHz with the main peak about 10.7 GHz. For $d_2 = 10.5$ mm the frequency range is $10.0 - 12.0$ GHz and the main peak is expected at 11.6 GHz. For the photonic crystals with a variable period which are assembled from two photonic crystals with the certain period in different sequence one can expect:

- for the combination d_1-d_2 the twice longer microwave signal with the spectrum close to the spectrum of photonic crystal with the period d_1.
- for d_2-d_1 combination the twice longer microwave signal accompanied by the spectrum widening to the lower frequency range.

Comparison of microwave signals for the photonic crystals with the fixed and variable periods (see Fig.5) demonstrates increase in the radiation pulse duration for the photonic crystal with the variable period. Measured power for the photonic crystal with the fixed period is about 35 kW, while for VFEL with the "grid" variable photonic crystal it is about 70 kW.

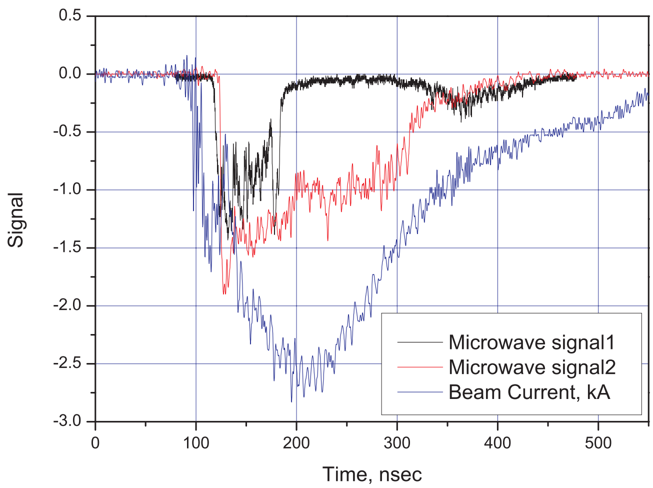

Figure 5: Comparison of microwave signals for the photonic crystal with the period d_1=10.5 mm (signal1) and the photonic crystal with the variable period $d_1 - d_2$=12.5-10.5 mm (signal2)

The measured radiation spectra for each of the two photonic crystals with the certain period are shown in Fig.6 for the period d_1 and Fig.7 for d_2. The measured frequency ranges for both cases correspond to those calculated.

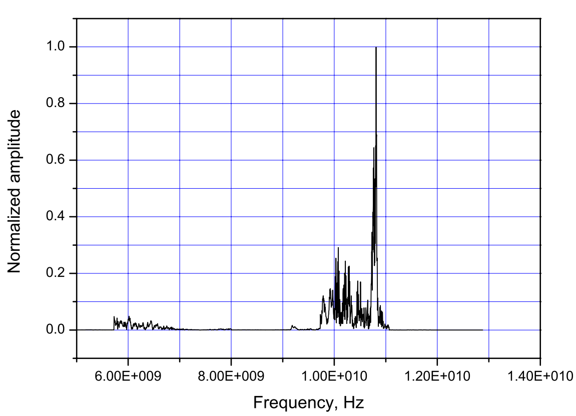

Figure 6: The spectrum for d_1 =12.5 mm

The measured radiation spectra for the photonic crystals with a variable period, which are assembled from the two photonic crystals with the certain period in different sequence are shown in Fig.8 and Fig.9. It is evident that the spectrum for the photonic crystal with d_1-d_2 (12.5-10.5 mm) combination is similar to that for the photonic crystal with d_1. Whereas the spectrum for the photonic crystal with d_2-d_1 (10.5-12.5 mm) combination is widened towards lower frequencies.

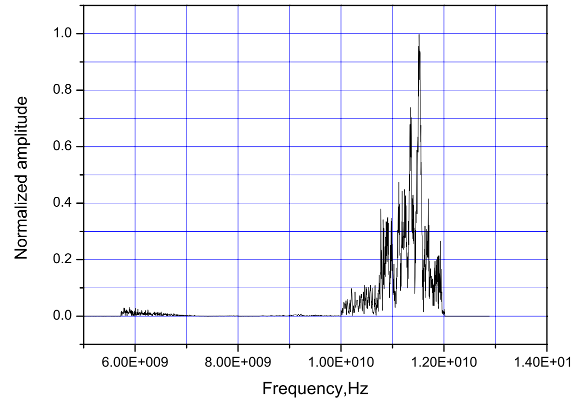

Figure 7: The spectrum for d_2 =10.5 mm

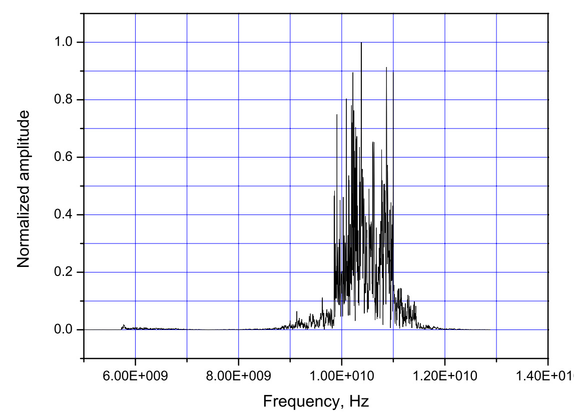

Figure 8: The spectrum for the photonic crystal with d_1-d_2 (12.5-10.5 mm) combination

CONCLUSION

Volume Free Electron Laser with a photonic crystal (crystal-like artificial periodic structure) formed by metallic threads periodically strained inside a cylindrical waveguide is studied. Experiments confirm that in accordance with the theory [8, 11], applying the photonic crystal with the variable period for VFEL operation one can expect the increase in radiation pulse duration and power. It is appropriate to mention here that the "grid" VFEL can operate similarly to a relativistic multiwave Cherenkov generator and the difference is that the former uses a solid electron beam and an interaction area occupies the whole volume of a resonator. On the contrary, the latter uses an annular electron beam and a surface interaction with a corrugated waveguide.

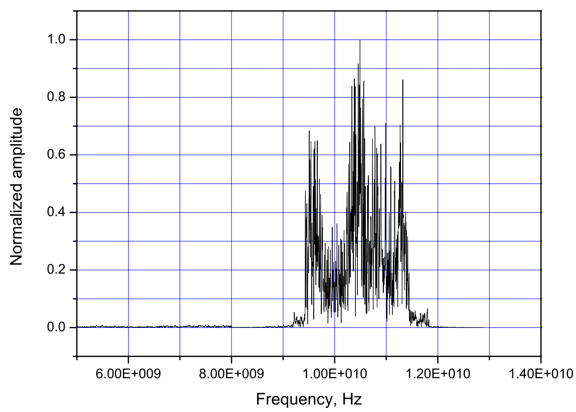

Figure 9: The spectrum for the photonic crystal with d_2-d_1 (10.5-12.5 mm) combination

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