Analysis of Frequency Spectrum in Planar Maser at ELMI Device

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Abstract – This paper presents the results of experimental investigation on spectrum of powerful 4-mm pulses generated in a planar free electron maser with hybrid resonator and optimized wave deflector at the ELMI-device. The measured spectrum of the radiation is in accord with the results of simulation and "cold" measurements of the resonator spectral properties.

1. Introduction

The experimental and theoretical research on generation of powerful 4-mm radiation is carried out at BINP (Novosibirsk) and IAP (Nizhnii Novgorod) [1]. Principal idea which these investigations are based on is a planar free electron maser (FEM) with longitudinal magnetic field. In such type of the maser the electrons of a sheet beam oscillating in the magnetic field of an active undulator, excite an electromagnetic wave and pump it to a high intensity level. For mode selection and synchronization of radiation generated by different parts of the sheet beam the two-dimensional distributed positive feedback was suggested and investigated [2]. This feedback is realized by using of planar Bragg structures with doubly periodic two-dimensional (2D) corrugation of the walls, on which a mutual scattering of electromagnetic energy fluxes propagating in forward, backward and transverse directions in relation to the E-beam motion is occurred. But for proper operation when the highest mode selectivity is accessible such structures should be opened in transverse directions. It leads to noticeable losses of the EM-wave energy and hence to a decrease of the resonator quality. To diminish such losses the hybrid resonator consisted of upstream 2D and downstream 1D Bragg structures which are connected by a piece of regular waveguide, was suggested [3]. In this case the amplification of a forward propagating EM-wave, which is synchronous with the electrons, takes place mostly in the regular section of the resonator and in the downstream 1D Bragg structure. As a result, the amplitude of the transversely propagating partial EM waves inside the input 2D structure becomes relatively small and EM-energy losses essentially decrease. Moreover the probability of the RF-breakdown significantly reduces in comparison with closed planar resonators consisting solely of 2D Bragg structures. At the same time, spatial coherence of the radiation from the oversized sheet electron beam can be still achieved via transverse energy fluxes inside the upstream 2D Bragg structure [3]. The radiation output after such resonator can be produced by a Bragg deflector suggested in [4], which allowed to turn radiation in the transverse direction and to separate it from the high-current electron beam in the collector section. In this case an optimization of the structure of the output wave and an increase in RF-power extraction from the resonator can be achieved by choosing of configuration of the corrugated area. In this paper we present the results of recent experiments carried out at the ELMI-device in which hybrid resonator and optimized wave deflector were used.

2. Electrodynamic System of the Maser

The schematic of the planar FEM used in the recent series of experiments at the ELMI-device is shown in the Fig. 1. The sheet electron beam with the cross section 0.4×7 cm and the current up to 3 kA is transported through the planar resonator in the undulator magnetic field. The undulator has the spatial period 4 cm. The amplitude of its transverse magnetic field can be varied from 0 up to 0.2 T, while the longitudinal field is practically homogeneous and is up to 1.4 T.

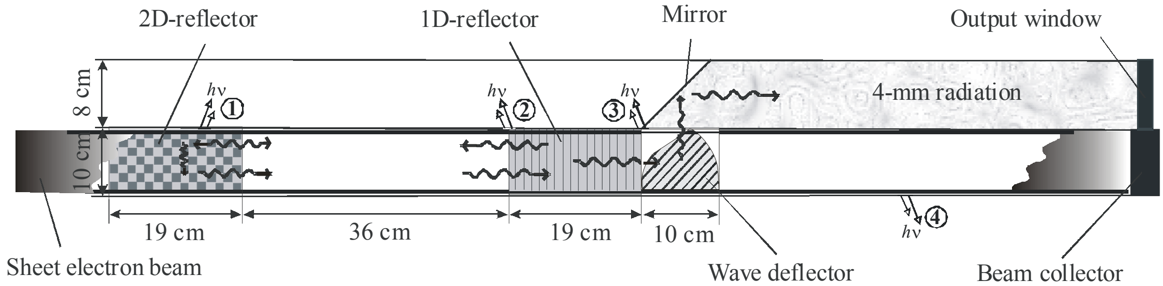

Fig. 1. Schematic of the planar maser experiments. 1–4 – mark the places of light emission registration

The hybrid resonator used in experiments consists of the upstream 2D and the downstream 1D Bragg reflectors, connected by a piece of regular waveguide with the cross section 0.95×10 cm and the length 32 cm. The upstream reflector formed by two parallel conducting plates with two-dimensional "chessboard" corrugation has the length 19 cm. The depth of its corrugation is 0.2 mm and the period in both directions is 0.4 cm. The downstream 1D Bragg reflector of the same length (19 cm) is consisted of two plates corrugated in one dimension with the depth of 0.07 mm.

Figure 2a shows results of computer simulations for the reflectivity of the hybrid resonator consisted of these two Bragg reflectors. Different lines refer to three values of the reflection coefficient (R) of the transverse ends of 2D reflector. As it is seen, in case of the "opened" 2D reflector ($R = 0$) only "longitudinal" modes of combined double-mirror resonator should exist. While in case of "closed" 2D reflector ($R = 1$) additional bands produced by establishing "transverse" modes between closed ends of reflector are appeared. The qualities of the "longitudinal" and the "transverse" modes are close to 500 and 2000 respectively. It is seen from the figure that the decrease of R leads to suppression of "transverse" modes and appearance of three "longitudinal" modes at the frequencies 74.6 GHz, 74.9 GHz and 75.3 GHz. The both types modes are registered in "cold" experiments for hybrid resonator with closed 2D reflector. To suppress the influence of the parasitic "transverse" modes on the resonator properties we put the microwave absorbers at the transverse ends of 2D reflector but we could only decrease the quality of "transverse" modes to the level of "longitudinal" and just this resonator was used in the experiments with sheet beam (Fig. 2b).

Together with novel hybrid resonator a new optimized wave deflector was used. The deflector was constructed of two 1D corrugated plates with the length 10 cm and a special shape of the corrugated area. The grooves of rectangular thread (depth 0.4 mm) were inclined under the angle 45° to the direction of the forward wave. By means of such thread this wave is scattered in perpendicular direction and output from the slit channel with E-beam. Then the wave is turned by a mirror to the single waveguide with cross section 0.95×9 cm. The shape of the corrugated area of the deflector was optimized to provide good matching of the scattered wave to H_{10} mode profile of the waveguide and to obtain high efficiency (0.9) of such conversion. This waveguide is ended by a horn and the radiation goes out to the atmosphere through the teflon window of 2.5 mm thickness and sizes 9×9 cm. As to the electron beam, after passing the resonator it moves in the output channel to the remote graphite collector located at 0.5 m distance from the resonator. Such long distance is intended to increase the time delay between the appearance of plasma on the collector and a rise of the plasma in the resonator. To control appearance and propagation of the plasma in the resonator and the output slit channel a set of light guides for registration of light emission from the plasma were located along electrodynamic system of the maser.

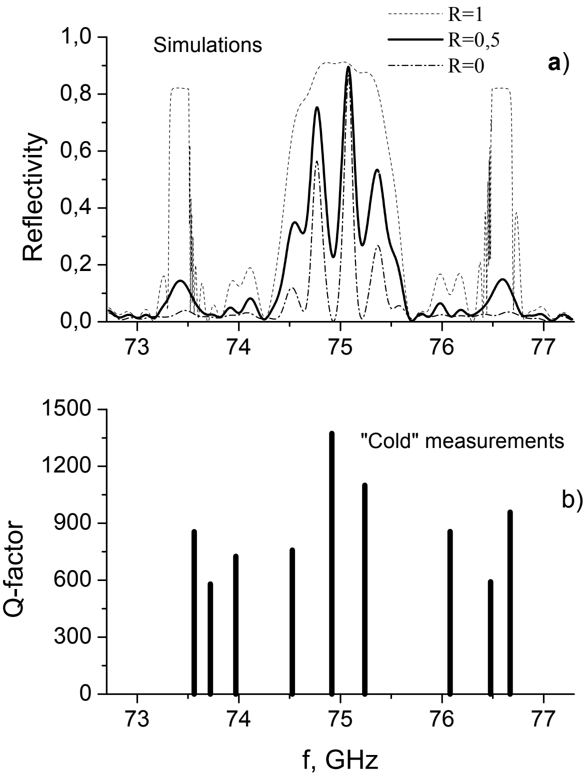

Fig. 2. Results of simulation for the reflectivity of the hybrid resonator (upper graph) and on measuring in "cold" experiments the Q-factors of resonator modes (lower one)

3. Experimental Results

Applying the hybrid resonator and optimized deflector to the maser a series of experiments on generation of 4-mm radiation was carried out. The main aim of this series was to measure a frequency spectrum of the radiation pulse. The amplitude of the transverse component of the undulator magnetic field was varied from 0 to 0.1 T and the longitudinal component was 1.2 T. The typical oscillograms of the diode voltage, the beam current, the microwave power and the light emission intensities from four points along the channel of the maser are shown in the Fig. 3. As it is seen the light emission starts firstly near the beam collector and this start is practically simultaneous with the beginning of the microwave generation. As moving from the collector to the upstream reflector the time delay of the light emission start increases. The plasma firstly appears near the beam collector, and then after half of microsecond it appears in the downstream 1D reflector ($h\nu_2$). At that moment the decrease of the microwave power starts and to the moment at which $h\nu_2$ signal reaches its maximum the microwave generation is closed.

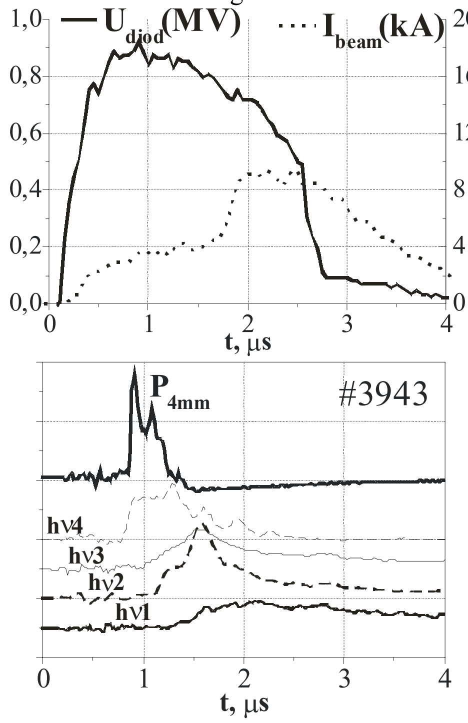

Fig. 3. Pulses of the diode voltage and the beam current (upper graph) with waveforms of the microwave power and the light emission signals from four marked places of the channel (lower one)

To analyse the radiation spectra the part of mm-wave radiation after passing the output window was transported by quasioptical waveguide to a special control room where it was analyzed by a set of spectral diagnostics. At the input of this diagnostic system the broadband resonance filter with the passband 72.3–77.4 GHz was placed. After this filter the radiation pulse was splitted by a directional coupler and one part was sent to the detector of a reference signal and the other part through a tunable bandpass filter to the detector. As the first variant of such filter the tunable interference Fabry-Perot filter with transmission band about 1 GHz was used. It is based on two parallel 11×11 cm 1D grids consisting of conductive stripes with width 0.4 mm and pitch 1 mm. The transmission band of the filter can be tuned from 72 up to 78 GHz by changing a gap between grids. The results of spectrum measurements by means of this filter are presented in the Fig. 4. As it is seen there are three bands of increased intensities in the spectrum, two side bands near 73 and 77 GHz correspond to excitation of “transverse” and central band near 75GHz – to the “longitudinal” modes that are imperceptible because of low resolution of the filter. As the second variant a narrow-band tunable filter based on the wavemeter with the bandwidth 0.1 GHz was used. In this case the entrance broadband filter was changed by narrow band resonant filter with passband 74.7–75.8 GHz in order to increase contrast ratio. An example of oscillograms registered by means of this filter is shown in the Fig. 5. The results of measurements by this filter also confirmed the existence of high spectral density near the mentioned frequencies but because of low contrast ratio of this filter the spectrum of the radiation could not be obtained. More precise analysis of radiation spectrum can be made by heterodyne method, based on mixing the generated radiation with the radiation of a precise generator with adjustable frequency which is now under process of tuning and data collection.

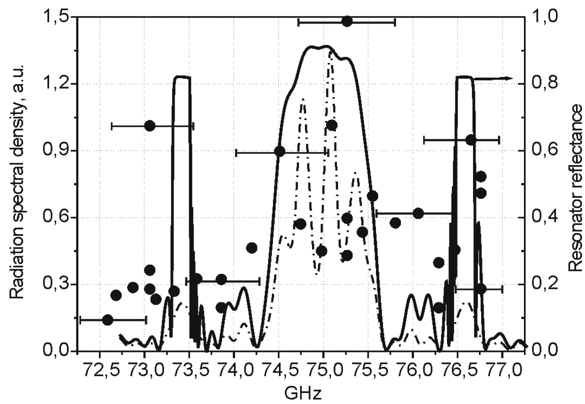

Fig. 4. Results of measurements of radiation spectral density (points) together with the results of simulation for the hybrid resonator reflectivity (solid and chain lines demonstrate the cases $R = 1$ and $R = 0.5$ respectively)

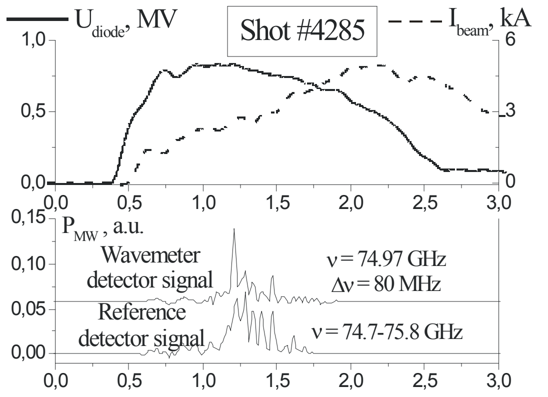

Fig. 5. Oscilloscope traces of the diode voltage and the beam current (upper graph) with signals of the reference detector and the detector after tunable filter on the base of wavemeter (lower one)

4. Conclusion

In the experiments on generation of 4-mm radiation in the planar FEM at the longitudinal magnetic field 1.2 T and the amplitude of the transverse field 0.07 T it was shown that in the case of hybrid resonator the main part of spectral density of the output radiation is concentrated in bands near the frequencies 73, 75 and 76.5 GHz which correspond to the “transverse” and “longitudinal” modes with maximal Q-factors obtained in the computer simulation. The temporal dynamics of the light emission from plasma in different parts of the maser was registered. The appearance of this plasma results in the decrease of the microwave power and pulse shortening.

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