JINR-IAP FEM OSCILLATOR WITH BRAGG RESONATOR

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A FEM-oscillator with a reversed guide magnetic field and a Bragg resonator as a RF radiation source for collider applications was studied. The configuration with a step of the corrugation phase is proved to be advantageous. It possesses such features as a high efficiency, precise tunability of the operating frequency and a narrow spectral band. It is demonstrated experimentally that such an oscillator is capable of operating at frequencies of ~30 GHz in single-mode regime with the frequency tuning in interval up to 6%. Frequency and spectrum measurements have been performed with precision of ~0.1%.

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1 INTRODUCTION

High-efficiency narrow-band free-electron lasers (masers) (FEL, FEM) can be used for the application as pulse microwave power sources suitable for testing the high-gradient accelerating structures of linear colliders. Recent investigations at JINR on this subject are oriented at the frequencies of ~30 GHz which corresponds to the frequency of the accelerating microwave field for the CLIC collider [1].

2 FEATURES OF FEM-OSCILLATORS USING DIFFERENT TYPES OF BRAGG RESONATORS

Since mid-1990s theoretical and experimental investigations of the FEM-oscillators with the Bragg resonators and reversed guide magnetic field are carried out at JINR in collaboration with RAS Institute of Applied Physics (N.Novgorod) [2, 3]. The distributed feedback in FEM is provided by Bragg reflectors – cylindrical waveguide sections with periodically corrugated inner surface.

Several schemes of the Bragg resonators under investigation are shown in Fig. 1. Initial experiments devoted to the traditional Bragg resonator with a smooth tube between the reflectors (Fig. 1a) showed that it was possible to obtain both the single-mode and multi-mode regimes of generation in such FEM-oscillators at different resonator Q-factor values in the steady-state mode of operation. The applying of such a FEM-oscillator scheme for supplying the high-gradient accelerating structures is coupled with certain technical problems. Particularly, it is difficult to provide fixing and precise tuning of the FEM frequency [4]. To solve these problems we investigated a FEM scheme, where the feedback was provided by Bragg resonators with a phase step of the mirror corrugation (Fig. 1b, c) [5, 6].

For a symmetrical resonator (Fig. 1b) with the corrugation phase shift equal to π there is the only high-quality oscillation in the reflection zone of the Bragg structures, located in the middle of this band (the central mode). The Q-factors of other oscillations at the edges of the reflection zone (so-called side modes) are considerably lower than that of the central mode. Thus the electrodynamic selection in a resonator with a corrugation phase step results in the excitation of only the central mode and occurring of the single-mode regime of operation already at the linear stage of the process.

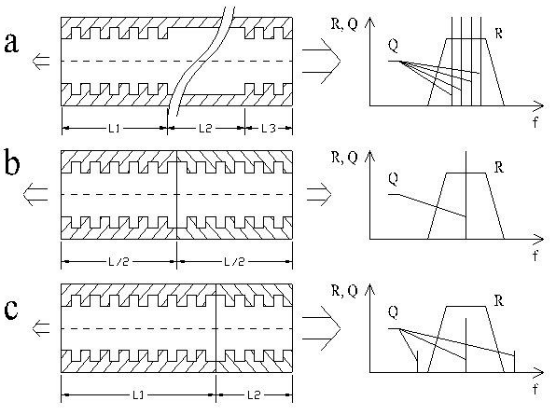

Fig. 1. The schemes of the Bragg resonators (on the left): a) double-optical resonator with a section of regular waveguide; b) symmetrical resonator with corrugation phase step; c) asymmetrical resonator with corrugation phase step. The reflection band and location of the frequencies of the resonator eigenmodes (on the right).

The equality of the microwave fluxes from the resonator in the forward and in the backward directions is a drawback of the symmetrical Bragg scheme. To enhance the power radiated in the forward direction it is profitable to use the non-symmetrical resonator configuration (Fig. 1c). However in such a scheme the Q-factors of the side modes grow, so the oscillator can be easier excited at those parasitic oscillations. Optimizing the corrugation depth and lengths of the Bragg reflectors we obtained higher efficiency [7].

3 PRECISE FREQUENCY TUNING IN FEM-OSCILLATOR

Besides the capability of providing the narrow-band RF radiation at a fixed frequency, a FEM-oscillator with a step in the corrugation phase also possesses the possibility of precise tuning of the operating frequency. For the corrugation phase shift between the Bragg reflectors equal to π the fundamental mode is positioned at the middle of the Bragg reflection zone. If the phase shift is varied from π to 2π (or to 0) the frequency of the fundamental mode drifts to the lower edge (or to the higher edge) of the Bragg zone. It is important to note that only one high-Q eigenmode exists inside the Bragg zone at any value of phase shift (if the value of the phase shift does not closely approach the limiting values 0 or 2π). Therefore high selective properties of the resonator are maintained in the major part of the resonator reflection band. ***Its width is proportional to the wave coupling coefficient of the Bragg structures*** [5]. As a result, inside this zone precise tuning of the oscillation frequency in an FEM is possible after mechanically changing the value of the phase shift between the Bragg structures.

The frequency tuning of a FEM oscillator was investigated by numerical simulations as well as in the experiments [4] for three different values of the phase shift between Bragg structures: π, π/2 and 3π/2. It was shown that the measured values of the central frequency and the frequency shift coincided, with an acceptable precision, with the simulation results. The experimentally obtained spectral distributions were too broad due to a low accuracy of the measurements at kW power level due to RF breakdown in the RF detector setup. To prevent RF-breakdown in the last series of the experiment the output RF signals were attenuated along the waveguide, which transmitted the radiation for a distance of ~ 30 m into the measuring room.

The FEM oscillator with a Bragg resonator is experimentally investigated at JINR using an induction linac LIU-3000 (electron beam energy 0.8 MeV, current 200 A, pulse duration 350 ns).

A schematic overview of the experimental setup is presented in Fig. 2. The electron beam was injected from the linac (1) with a repetition rate of 0.5 Hz into the FEM oscillator (2) immersed in a solenoid. A wiggler with a period of 6 cm producing the transverse helical magnetic field was used to pump oscillating velocity to the beam.

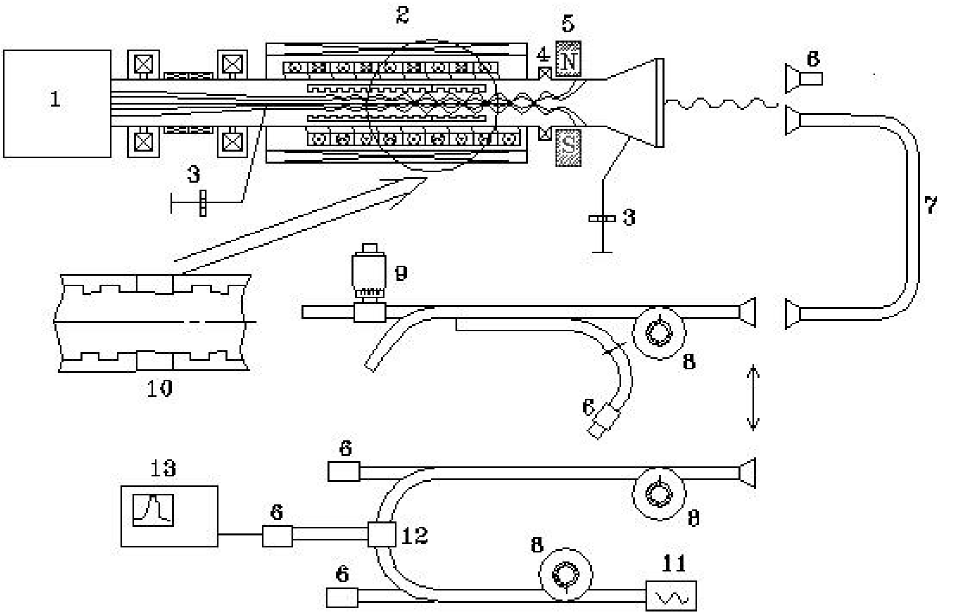

Fig. 2. Scheme of the experiment: 1) accelerator LIU-3000 as the electron beam injector; 2) FEM oscillator; 3) Rogowski coil; 4) isolator; 5) deflecting magnet; 6) calorimeter; 7) crystal detector of the microwave power; 8) attenuator; 9) wavemeter with the precise tuning of the resonant frequency; 10) insertion ring; 11) master oscillator; 12) RF frequency mixer; 13) digital oscilloscope.

The Bragg resonator was composed of two waveguide sections of equal lengths of 170 up to 197 mm, having a rectangular corrugation of period $d = 5.64$ mm and depth $a_1 = 0.5$ mm. This corrugation provided a selective feedback at an operating frequency range near 30 GHz by coupling the operating H_{11}-mode and the backward E_{11}-mode of a circular waveguide. Precise tuning of the oscillation frequency in the FEM was performed by inserting short sections of a smooth waveguide between the reflectors. For an insertion ring (10) of length l the value of the phase shift is $\Delta\varphi = 2\pi l/d$.

After the interaction region the beam was dumped onto the waveguide under the influence of the transverse magnetic field produced by the permanent magnet (5). The beam current was measured by Rogowski coils (3) at the FEM waveguide input and output. Measurements of the time dependence of the microwave power were carried out by calibrated semi-conductor crystalline detectors (6).

Precise measurements of the radiation frequency and spectrum were carried out after transportation (7) of the radiation into a measuring room and after attenuation to the milliwatt level. Two measurement techniques were used: a narrow-band tunable band-pass waveguide filter (9) and heterodyne mixing (11, 12).

The accuracy of the frequency measurement with the tunable filter was about 0.1%. To obtain the radiation spectrum using the filter consecutive measurements had to be done by adjusting the resonant frequency of the filter during a series of RF-pulses. In contrast, the heterodyne technique allowed measuring the spectrum of a single RF-pulse. The accuracy of the heterodyne technique was determined by the error in the master oscillator frequency. So, combining both measurement techniques, we can determine the absolute value of the operating FEM frequency with a precision of about 0.1% and obtain a precise shape of a RF-pulse spectrum.

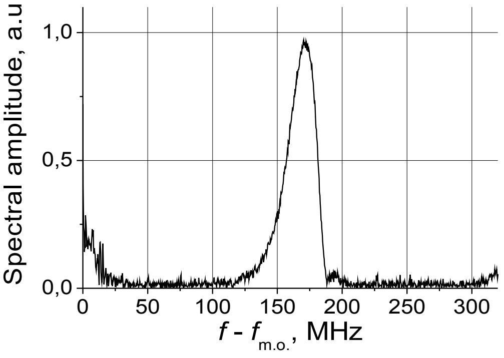

Fig. 3. The RF pulse spectrum obtained by the heterodyne technique ($f_{\text{m.o.}}$ is the master oscillator frequency).

The operating frequency and spectrum of the FEM output radiation were measured for various lengths of the insertion ring in the resonator. Figure 3 presents the spectrum of the output heterodyne signal for a corrugation phase shift $\Delta\varphi = \pi$. The FEM operating frequency is measured to be 29.98 GHz in this case. It is in a good agreement with the value measured using the resonant filter. The spectral band was found to be about 30 MHz (FWHM), i.e. close to the spectral resolution of the filter. This value corresponds to the approximation $\Delta f/f_0 \approx Q^{-1}$ where Q is the resonator quality factor which is equal to about 10^3 in our case.

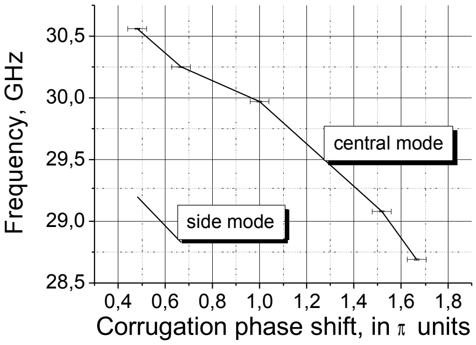

Fig. 4. Dependence of the frequencies of the FEM oscillator modes on the value of the corrugation phase shift between Bragg reflectors.

The dependence of the frequency of the "central" mode on the phase shift between the reflectors is shown in Fig. 4 (upper curve). The range of phase shift covers most of the Bragg reflection zone of the resonator, so the tuning range of about 6% has been achieved. The errors shown in Fig. 4 were defined mainly by mechanical tolerances in manufacturing and mounting the insertion ring. They increase the uncertainty of the frequency setting up to ~0.15%. The type of $f(\Delta\varphi)$ dependence is close to linear which is in a good agreement with previous simulations and preliminary experimental results [4].

For phase shift values deviating significantly from π, excitation of "side" eigenmodes of the resonator (i.e. positioned just outside the Bragg reflection zone) is also possible [7] and, indeed, was observed in some regimes at the proper initial mismatches from synchronism (i.e. proper wiggler and/or guide fields). The results of measurement for the low-frequency side-mode are also presented in Fig. 4 (lower curve).

4 CONCLUSIONS

A possibility of creating a high-efficiency, precisely tunable, narrow-band ($\delta f/f \sim 0.1\%$) FEM-oscillator using the reversed guide magnetic field and Bragg resonator has been proved. It has been demonstrated experimentally that an oscillator with the step of the corrugation phase is capable of operating at frequencies of ~30 GHz in single mode-regime with the frequency tuning in interval up to 6%. Frequency and spectrum measurements by the tunable band-pass waveguide filter and with the heterodyne technique have been performed with precision of ~0.1%. The results on the precise frequency tuning are in a good agreement with the previous simulations and experiments.

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