High-Efficiency Single-Mode Free-Electron Maser Oscillator Based on a Bragg Resonator with Step of Phase of Corrugation

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A new type of high-selective Bragg resonator having a step of corrugation inside the interaction region was used as a microwave system for a free-electron maser (FEM). Using a LINAC LIU-3000 (1 MeV/200 A/200 ns) to drive the FEM oscillator, a single-mode single-frequency operation was achieved at a frequency of 30.74 GHz with an output power of about 50 MW, which corresponded to a record efficiency of 35% for a millimeter wavelength FEM.

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One of the promising sources of powerful coherent Ka-band radiation is free electron masers (FEMs) with a guide magnetic field. For oscillator schemes of FEMs Bragg resonators were first suggested in [1,2] and in the millimeter wavelength band may be constructed from waveguide sections which have weak corrugations on the side walls [3,4]. The use of Bragg resonators allowed the realization of narrow-band FEM oscillators operating in the millimeter wavelength band [2,5–8]. These experiments were based on a two-mirror scheme of the Bragg resonators. In this scheme the Bragg structures were associated with selective reflectors which were separated by a regular waveguide section, where the main interaction between beam electrons and rf field occurred. In particular, a Bragg resonator of this type was used in the FEM oscillator realized in collaboration between Joint Institute for Nuclear Research (JINR) (Dubna, Russia) and the Institute of Applied Physics, Russian Academy of Sciences (IAP RAS) (Novgorod, Russia) which was driven by a LINAC LIU-3000. In these experiments at the frequency of 31 GHz in the regime of a reversed guide magnetic field, an output power of 35 MW, which represented an electron efficiency of about 25%, was obtained [9,10]. This efficiency outstrips the efficiency of previous Bragg FEM-oscillator experiments which used a guide magnetic field [2,5–8]. In an optimal Q-factor resonator single-mode single-frequency operation was realized. In accordance with computer simulations this regime established at a nonlinear stage of evolution, when one of the longitudinal modes grew and suppressed other modes (which are excited by the electron beam at the linear stage) due to a nonlinear mode competition mechanism. However, the computer simulations as well as experimental data show that even in this optimal Q-factor resonator small changes in the beam parameters (energy, transverse and longitudinal velocities, etc.) lead to the realization of a stationary regime at different longitudinal modes of the resonator (these modes are positioned inside the frequency zone of effective Bragg reflection and have a very small difference in frequencies and Q factors). This fact may be considered as a drawback of such a type of resonator scheme, because inevitable jitter of the beam energy and pulsed magnetic field strength will result in a change in oscillation frequency during single microwave pulse as well as from pulse to pulse. At the same time some possible applications of high-power microwave generators require high stability in the radiation frequency. In particular, high frequency stability together with high power are needed for driving high-gradient structures in the next generation of accelerators [11].

This problem may be solved using an alternative Bragg resonator scheme suggested in [3], i.e., a Bragg resonator with a step of phase of corrugation inside the interaction region. This resonator consists of two Bragg structures (without regular waveguide section between them) having a step of phase π between the corrugations at the point of connection (Fig. 1). This resonator possesses only one eigenmode which is situated inside the zone of effective Bragg reflection. The frequency of this fundamental mode is equal to a precise Bragg resonance frequency and the Q factor of this mode greatly exceeds the Q factors of other modes which are positioned outside the effective Bragg reflection zone. Thus, the selective properties of a resonator of this type are significantly improved in comparison with a two-mirror Bragg resonator. At the same time, the high Q factor of the fundamental mode allows a decrease in interaction length which results in an increase in efficiency while simultaneously reducing sensitivity of the FEM to the initial spread of beam parameters.

Preliminary dynamics of Bragg FEM operation was studied theoretically. Time domain analysis taking into consideration the dispersion properties of the Bragg structures was used [12]. The numerical simulation of excitation of a FEM by an electron beam and oscillation buildup was performed for parameters close to the experimental conditions. In difference with [12] space charge effects were included into the simulations in the frame of a 1D model. The beam charge parameter corresponded to the operation of the FEM on the boundary of Raman and Compton regimes. Under such conditions it had some

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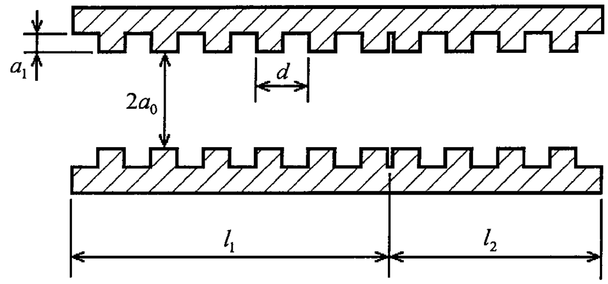

FIG. 1. Scheme of Bragg resonator with step of phase of corrugation.

small influence of the space charge on the output power, while the radiation spectrum was defined by properties of the "cold" resonator and was practically the same as in the case of zero space charge.

Figure 2(a) presents a time dependence of efficiency for a moderate Q-factor resonator. Electrodynamic mode selection taking place in the resonator leads to the establishment of the fundamental highest Q mode, practically without other "parasitic" modes even during the transient stage.

It should be noted that, simultaneously along with the highest Q-factor mode at the Bragg frequency, additional modes with frequencies positioned out off the effective Bragg reflection zone are also present in the spectrum of the resonator with a step of phase of corrugation. These "side" modes are associated with the modes of the separated Bragg structures which form the resonator. Increase

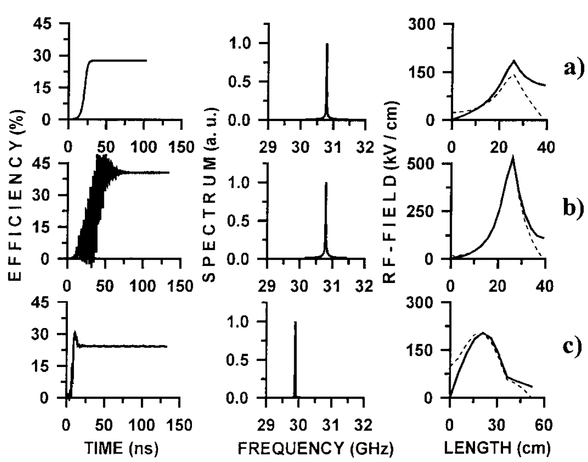

FIG. 2. Computer simulation of excitation of the FEM oscillator with Bragg resonator having a step of phase of corrugation for different resonator configurations: (a) $l_1 = 26$ cm, $l_2 = 13$ cm, $a_1 = 0.4$ mm, $B_0 = -0.18$ T; (b) $l_1 = 26$ cm, $l_2 = 13$ cm, $a_1 = 0.6$ mm, $B_0 = -0.18$ T; (c) $l_1 = 39$ cm, $l_2 = 13$ cm, $a_1 = 0.6$ mm, $B_0 = -0.16$ T ($E_{\mathrm{beam}} = 0.8$ MeV, $I_{\mathrm{beam}} = 170$ A, $B_w = 0.1$ T). Left column: time dependence of efficiency. Middle column: spectrum of radiation in the stationary regime of oscillations. Right column: longitudinal structure of partial waves in the stationary regime of oscillations. Solid lines correspond to synchronous to electrons wave ($TE_{1,1}$ wave) and dashed lines to backward wave ($TM_{1,1}$ wave).

in a wave coupling coefficient on the Bragg structures (i.e., corrugation depth) leads to an increase in Q factor of these modes until, finally, the threshold of generation at these modes is exceeded. In such a situation at the transient stage excitation of different—fundamental as well as side—modes take place. However, later during the nonlinear stage the fundamental highest Q mode suppresses all other modes due to a nonlinear mode competition mechanism. This results in a single mode being established [Fig. 2(b)] and, consequently, stationary single frequency operation at the Bragg frequency. Moreover, for optimal parameters of the resonator the stationary regime of oscillation is established at this highest Q mode for any mismatches of synchronism inside the zone of self-excitation. Thus, frequency stability of oscillation is significantly improved in a Bragg resonator with a step of phase of corrugation. It is important also that the longitudinal field structure in a resonator of this type [Fig. 2(b)] is more favorable for efficient energy extraction from the electron beam. As a result, efficiency of the FEM increases by approximately 1.5 times in respect to a conventional two-mirror Bragg resonator scheme.

For an experimental study a Bragg resonator was designed in the form of two cylindrical waveguide sections of inner diameter 22 mm having corrugations on the inner waveguide wall of a 5.4 mm period. A step of phase π between the corrugations on the two sections took place at the point where both Bragg structures were connected. A $TE_{1,1}$ wave of the circular waveguide was chosen as the operating mode and for optimal parameters the resonator was designed for reflections of the operating wave into the backward $TM_{1,1}$ wave at a frequency near 31 GHz. The result of calculation of the reflection coefficient from the Bragg resonators with a step of phase of corrugation (for the geometry where the maximum output power was observed in the experiments) is compared in Fig. 3(a) with the result of cold measurement. The resonator eigenmodes correspond to minimums in the reflection coefficient for the given method of measurement. As one can see in Fig. 3(a), the width of zone of effective Bragg reflection and, therefore, the wave coupling coefficient at the Bragg structures [4] are in good agreement with the results of calculations. Measured in the cold tests frequency of the highest Q mode was 30.74 GHz. The Q factor for the fundamental mode was about 1500 that corresponded to calculated value.

An experimental study of the FEM was performed on the LINAC-3000 (JINR, Dubna) which generated electron energies of 0.8 MeV and a 200 A beam current pulse of duration ~200 ns at a repetition rate up to 1 Hz. A klystron-like electron gun with the magnetically shielded oxide thermoionic cathode was used. At the exit of the accelerator there are three magnetic lenses and two correctors of the transverse position of the beam for matching it with the solenoid. This method provides electron beam formation with the initial energy spread of about (1–2)%. The

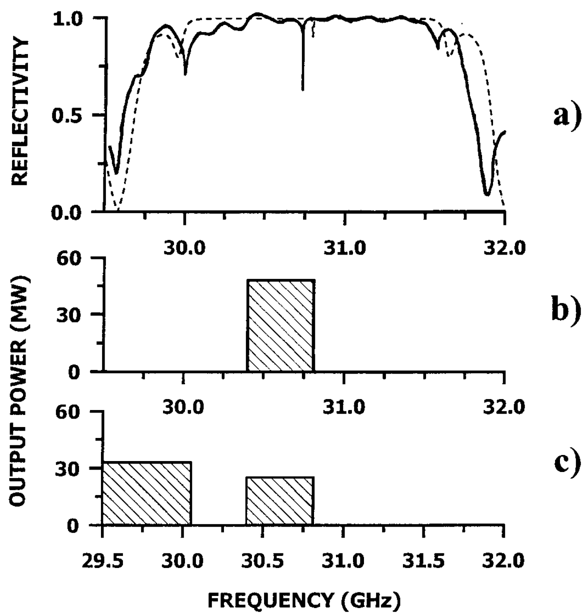

FIG. 3. (a) Reflection coefficient of Bragg resonators with step of phase of corrugation versus frequency (solid line—"cold" microwave measurement; dashed line—calculations) for $l_1 = 26$ cm, $l_2 = 13$ cm, $a_1 = 0.6$ mm. (b),(c) Result of frequency measurement using a set of cut-off waveguide filters in "hot" experiments for the resonators of different geometry [(b) $l_1 = 26$ cm, $l_2 = 13$ cm and (c) $l_1 = 39$ cm, $l_2 = 13$ cm ($a_1 = 0.6$ mm)]. Dashed zones present frequency intervals in which radiation frequency was detected; amplitude of the dashed zones correspond to the maximum output power observed.

helical wiggler with a period of 6 cm and amplitude of the transverse magnetic field on the axis up to 3.5 kG was used to pump the oscillation velocity to the electrons. The wiggler field was slowly up-tapered over the initial six periods providing an adiabatic entrance for the electron beam. The wiggler was immersed in a uniform axial magnetic field generated by a solenoid. The strength of this field could be varied up to 7 kG with the added possibility to vary the direction of the guide field.

The electron beam currents on the input and the output of the interaction region were measured by Rogowski coils. The output rf power was measured using calibrated "hot carrier" semiconductor detectors. The detectors were calibrated using a magnetron and checked in parallel with several calorimeters. The accuracy of the detectors' calibration using the different methods gives us the relative uncertainty in the absolute power measurements of $\pm 10\%$. A set of waveguide cut-off filters (which were calibrated using a sweeping frequency testing oscillator) was used to measure the radiation frequency in the FEM with an accuracy of (1–2)% for different frequency regions.

A regime of reversed guide magnetic field [13,14] was chosen for the FEM operation. In this regime the rotation of the electrons in the helical wiggler field is opposite to the cyclotron rotation in the guide field (marked by "$-$" sign further). Computer simulations [10,15] show that these far from cyclotron resonance regimes provide high-quality beam formation in tapered wiggler section and have low sensitivity to the initial spread of beam parameters resulting in high-efficiency e-beam/e.m. (electromagnetic) wave energy extraction. This fact is corroborated by the results of previous FEM amplifier [13,14] and oscillator [9,10] experiments where maximal efficiency was obtained under the reversed guide field orientation.

In the experiments carried out, radiation, at the designed circularly polarized $TE_{1,1}$ wave, was detected. The duration of the rf pulse was about 50–100 ns. In accordance with simulations the highest radiation power as well as the narrowest bandwidths were realized at a frequency around 31 GHz. Selecting the operating regime and tuning to the maximum output power were achieved by changing both the wiggler (B_w) and guide (B_0) fields that resulted in a change in longitudinal velocity of beam electrons and, thus, bounce-resonance conditions. The resonator parameters were optimized by using the Bragg structures of different lengths l_1 and l_2 as well as depths of corrugation a_1.

The highest radiation power of 48 ± 5 MW was obtained at a frequency of 30.74 GHz when the resonator consisted of Bragg structures of length 26 and 13 cm. In this experiment the beam current was 170 A and, thus, an electron efficiency of about 35% was achieved. Results of spectrum measurements are presented in Fig. 3(b). The dashed zone represents the frequency interval between two filters having neighboring cut-off frequencies in which the radiation frequency was detected. Comparison of the frequency measurements with the mode spectrum found in the cold microwave experiments [Figs. 3(a) and 3(b)] shows that only one, the highest Q eigenmode of the resonator, lies inside the measured frequency zone. It should be noted that computer simulations demonstrate that the frequency generated is not shifted notably from the eigenfrequency of the cavity modes. Thus, it can be concluded that a single-mode single-frequency operation was realized in the high-efficiency operating regime of the FEM. It is important to note that for the optimal parameters of the resonator in accordance with simulations [compare with Figs. 2(a) and 2(b)] the oscillations at the highest Q mode at the Bragg frequency were observed for any fields B_w and B_0 (i.e., for any mismatches from bounce resonance inside the zone of self-excitation). In the highest efficiency regime the wiggler and guide fields amounted to $B_w = 0.12$ T and $B_0 = -0.21$ T, respectively.

A shift in the position of the step of phase to the middle of the resonator (i.e., when the Bragg structures of equal lengths were utilized) leads to a drop of output power. For a symmetrical cold resonator the structures of forward and backward partial waves for the highest Q mode are bilaterally symmetrical [3]. The partial waves stay approximately symmetrical when excited by the electron beam also, and this results in equality of the upstream and downstream e.m. energy fluxes. In the case of an unsymmetrical resonator, when a step of phase is positioned closer to the collector side of the resonator, the downstream flux may greatly exceed the upstream one and, thus, in practice a single output of radiation is possible [compare with Figs. 2(a) and 2(b)].

It should be noted that an increase in the length of one of the Bragg structures leads to a further increase in the Q factor of the side modes. It results in a situation where the Q factor for these modes may be the same as for the fundamental mode. Computer simulations demonstrated that in this case the stationary regime of generation may be realized at the fundamental as well as at the side modes [Fig. 2(c)]. However, even in this case of nonoptimal resonator with step of phase of corrugation, the frequency distance between the modes is about half of the zone of effective Bragg reflection and for the discussed parameters 2–3 times higher than in a two-mirror resonator. Thus, the change in the mismatch of synchronism shifting oscillations from fundamental to side modes should be rather high. Therefore, requirements for the stability of parameters of an accelerator and an electron-optical system are reduced and thus can be realized more easily in practice.

As theoretically predicted, separate oscillation regimes at the fundamental as well as at the side modes were observed in the experiments when the length of the cathode side Bragg structure was increased up to 39 cm. For this nonoptimal resonator results of power and spectrum measurements in the frequency region from 29.5 to 32 GHz are given in Fig. 3(c). Selection of operation at the different modes was realized by varying both the wiggler B_w and guide B_0 fields to optimize the bounce-resonance conditions for every mode [compare with Fig. 2(c)]. Excitation of the side mode with frequency of 30.06 GHz was observed for a guide field $B_0 = -0.18$ T and a wiggler field $B_w = 0.11$ T. Measured in cold tests the Q factor for this mode was 1000.

In summary, in the experiments carried out a Bragg resonator with a step of phase of corrugation inside the interaction region was shown to successfully operate as a novel microwave system for a millimeter wavelength FEM. The FEM parameters under which microwave generation was observed as well as the measured parameters of output radiation were in good agreement with numerical simulations. Under the optimal parameters of the resonator at the frequency of 30.74 GHz the output power was about 50 MW, corresponding to an efficiency of 35%. It is important to note that high efficiency was realized at the full current produced by the accelerator (without the need to reduce the current in the beam). High efficiency as well as narrow spectrum width were achieved because of the high quality of the helical electron beam formed in the reversed guide field regime as well as the selective properties of the Bragg resonator.

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