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Powerful narrow-band relativistic masers with Bragg resonators operating from mm to sub-mm wavelength band: resent results and prospects

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Introduction

By now, powerful narrow-band free-electron maser (FEM) operating at mm wavelength band has been realized in collaboration between JINR (Dubna) and IAP RAS (N.Novgorod) [1]. The radiation parameters achieved allows JINR-IAP FEM to be used in several applications including testing of components for high-gradient accelerators, biology-medical studies, physics of nanoparticles, etc [2]. The aim of present work is development of narrow-band relativistic masers operating up to sub-mm wavelength bands at MW/multi-MW power level for potential applications.

As an FEM microwave system capable to provide stable narrow-band operation in strongly oversize interaction space, we proposed high-selective Bragg resonators of the novel type based on the so-called advanced Bragg structures with the feedback loop involving propagating and quasi-cutoff waves [3, 4]. To decrease Ohmic losses associated with excitation of cut-off mode it is attractive to use two-mirror resonator scheme with the up-stream advanced Bragg reflector and conventional Bragg reflector with rather small reflectivity as a down-stream reflector (Fig. 1).

FEM-oscillators operating from Ka- to W-band

The JINR-IAP FEM is driven by induction linac LIU-3000 0.8 MeV / 200 A / 250 ns /1 pulse/s (JINR). A reversed guide magnetic field regime is used for the FEM operation. This regime possesses low sensitivity to the initial beam spread and, as a result, is optimal for high-efficiency FEM operation. For operation from Ka- to W-bands, helical wigglers having periods from 6 cm to 3 cm correspondingly were constructed. Enhance in amplitude of the transverse magnetic field in short-period wigglers alongside with refining its transverse homogeneity was achieved by optimization of the currents distribution in the wiggler winding. To improve the quality of helical electron beam formation at short wavelengths, the slowly up-tapered wiggler entrance was optimized as well [5].

For operation at 30 GHz, advanced Bragg resonator was constructed with the oversized parameter $\varnothing/\lambda \sim 2$ and included advanced Bragg reflector with a feedback loop formed by two counter-propagating $TE_{1,1}$ waves and cutoff $TE_{1,2}$ wave (Fig. 2). Resonator for V-band (60 GHz) was composed with advanced up-stream Bragg reflector operating with feedback loop $TE_{1,1} \leftrightarrow TM_{1,2}$-cutoff $\leftrightarrow TE_{1,1}$ at the oversize parameter $\varnothing/\lambda \sim 3$ (Fig. 4). For W-band (80 GHz) advanced Bragg reflectors based on excitation of the feedback cutoff wave of $TE_{1,5}$ – type were designed to provide an effective FEM operation at oversize parameter $\varnothing/\lambda \sim 5$ (Fig. 5). In accordance with the 3D simulations, effective narrow-band reflections were demonstrated in "cold" test of Bragg structures of the novel type. In all resonators (manufactured for operation from Ka- to W-band) the reflection band in advanced Bragg structures was measured 0.5–0.7 GHz with maximum power reflection up to 80–90%, while the conventional structures had ~60% reflection in much broader band of 2.5–3 GHz.

In the proof-of-principle experiments at LIU-3000 a narrow-band operation of novel scheme of FEM-oscillators was obtained under design parameters. At Ka-band, stable single-mode operation at the frequency of 30.2 GHz was observed in accordance with simulations. The output power amounted up to 20 MW (efficiency about 15–20%) with the spectrum width of 6–7 MHz (measured by heterodyne technique) close to the theoretical limit (Fig. 3).

In the experiments at V- and W-band, the radiation spectrum was measured by means of cut-off filters set with the accuracy of about 1 GHz. Both FEM demonstrated the oscillation frequency belonging to the designed feedback loop of the hybrid resonator in the vicinity of 59 GHz and 80 GHz correspondingly.

In the resonators of optimal geometry the output power (measured by calorimeter) in both frequency regions amounted to 5–7 MW when the beam current was about 70 A (Fig. 6), which corresponded to the electron efficiency of up to 10–12%.

Project of sub-mm CARM-oscillator

Further increase of the radiation frequency in FEM is restricted by the wiggler period. As a potential candidate to advance into sub-mm wavelengths an another type relativistic maser, namely, cyclotron autoresonance maser (CARM) is attractive. Project of 250 GHz MW-power CARM operating in quasi-cw regime is under development at ENEA Frascati [6] aimed on compact plasma fusion reactors with high magnetic field. Modelling short-pulse CARM experiment is under development at LIU-3000 facility.

For this project we consider cylindrical cavity with diameter $\varnothing/\lambda \sim 7$–$10$ that seems sufficient for the intense beam transportation and heating demand during RF-pulse for designed powers. In specified waveguide a $TE_{1,2}$ wave was chosen to provide needed electron bunching parameter $\mu = 1 - \beta_{ph}^{-2} \approx 0.1$ and effective interaction with the beam having oscillating velocity $\beta_\perp \sim 0.4 - 0.5$ at the axial magnetic field of about 5–6 T. According to 3D simulations using code CST "Microwave Studio", advanced Bragg structure of given transverse size and about 3–5 cm long is able to ensure needed selectivity and high reflection at designed frequency band (Fig. 7).

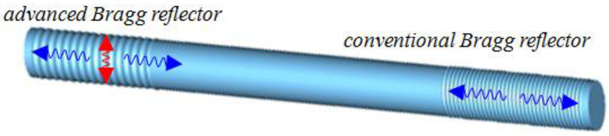

Fig. 1. Scheme of hybrid two-mirror resonator based on advanced and conventional Bragg reflectors. The partial wave-fluxes in both reflectors are shown by the arrows

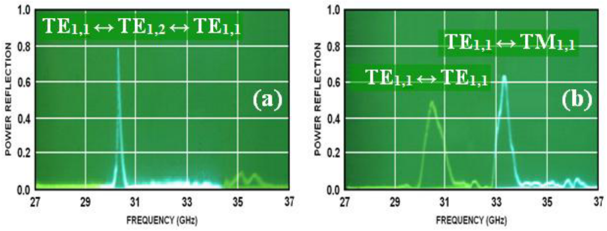

Fig. 2. Results of "cold" tests of (*a*) advanced ($l_{adv} = 15$ cm) and (*b*) conventional ($l_{con} = 8$ cm) Ka-band Bragg reflectors

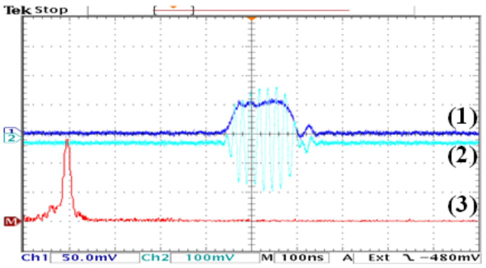

Fig. 3. Results of JINR-IAP FEM experiments in Ka-band. Typical oscilloscope traces of (1) RF-pulse (100 ns / div.), (2) heterodyne beating signal and (3) frequency spectrum (50 MHz / div.)

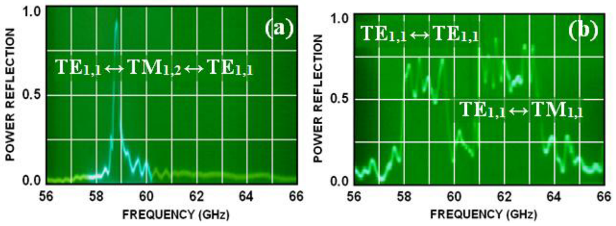

Fig. 4. Results of "cold" tests of (*a*) advanced ($l_{adv} = 12$ cm) and (*b*) conventional ($l_{con} = 8$ cm) V-band Bragg reflectors

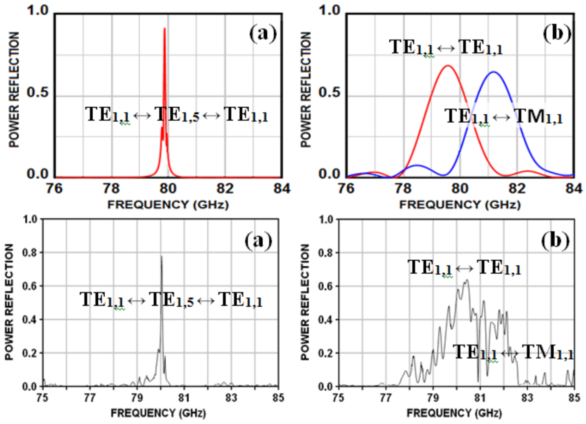

Fig. 5. Results of 3D simulations (top) and "cold" tests of Bragg structures of different types at W-band. Frequency dependence of reflection of (*a*) advanced ($l_{adv} = 12$ cm) and (*b*) conventional ($l_{con} = 8$ cm) reflectors

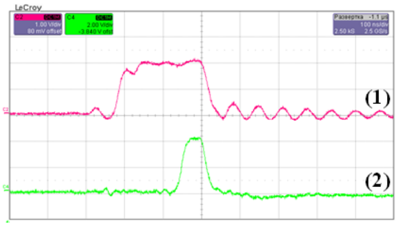

Fig. 6. Results of the JINR-IAP FEM experiments in W-band. Typical oscilloscope traces of (1) beam current and (2) output RF-pulse (100 ns / div.)

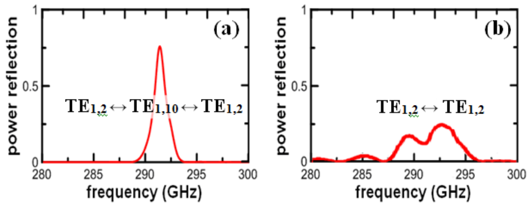

Fig. 7. Results of 3D simulations of (*a*) advanced (Ø/λ ~ 10, $l_{adv} = 5$ cm) and (*b*) conventional (Ø/λ ~ 7, ($l_{con} = 3$ cm) Bragg reflectors in 300 GHz frequency range

Theoretical analysis carried out proved operability of a narrow-band CARM operation for parameters given above. To suppress self-excitation at "parasitic" low-frequency near-cutoff modes periodical slits in the cavity were considered [7]. For designed parameters simulations demonstrated establishment of a narrow-band oscillation regime with MW-power level and efficiency of 25–30% in the cavity of 6–8 cm long and initial velocity spread in the beam did not exceeding 1–2% [8].

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