Free-electron masers with Bragg resonators

I. E. Botvinnik, V. L. Bratman, A. B. Volkov, N. S. Ginzburg, G. G. Denisov, B. D. Kol'chugin, M. N. Ofitserov, and M.I. Petelin
Institute of Applied Physics, Academy of Sciences of the USSR

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Application of highly selective open resonators, based on resonant scattering of waves by corrugated metallic walls, allowed realizing efficient ("high-current") free-electron masers: the ubitron and, for the first time, a maser based on the cyclotron autoresonance.

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The use of a doppler transformation of the emission frequency of electron oscillators propagating with relativistic translational velocity $\mathbf{v}_{\|}$, first proposed in Ref. 1,

$$\omega = \mathbf{k}\mathbf{v}_{\|} + \Omega \tag{1}$$

has given rise to several classes of coherent and quasicoherent sources of electromagnetic waves in the range 1-10^{-11} cm [in (1), $\omega_1\mathbf{k}$ are the frequency and wave vector of the wave, and Ω is the oscillation frequency of the particles]. The corresponding sources of coherent (collective, stimulated) radiation, namely, free-electron lasers and masers (FEL and FEM), provide radiation with pulse power of the order of 10^4 W at a wavelength 3.4 μm^2 and 10^6 - 3×10^7 W at wavelengths from 1 cm to 0.4 mm (see, for example, Ref. 3). However, FEL and FEM, which use high-current electron accelerators as injectors,[3] have a low efficiency and low degree of signal coherence because of the absence (in the superradiant mode) or inadequacy of the feedback systems.

The main difficulty in developing electrodynamic systems equal to high-current FEM and FEL lies in the necessity of simultaneously satisfying the requirements that the system (1) provide selective excitation of the mode formed by the flux of rays, which would propagate at a small angle ϕ to the translational velocity of the particles[1]: $\phi \lesssim \gamma^{-1}$ (γ is the relativistic factor for electrons); and, (2) transport an intense electron beam. The problem can be solved by using highly selective resonators in the form of a segment of a metallic wave guide with a corrugated side wall,[4] where under the Bragg condition

$$k^{+}_{\|} - k^{-}_{\|} \simeq 2\pi/d \tag{2}$$

resonant scattering of waves is realized ($k^{\pm}_{\|}$ are the longitudinal wave numbers of waves moving in the same direction and opposite to the electrons, and D is the spacing of the corrugations).

In addition to the development of the electrodynamic systems, the development of FEM and FEL must include the development of an active substance. Evidently, each type of injector and each frequency range must correspond to its own most convenient method for imparting an oscillatory motion to the electrons. Electrons oscillating with

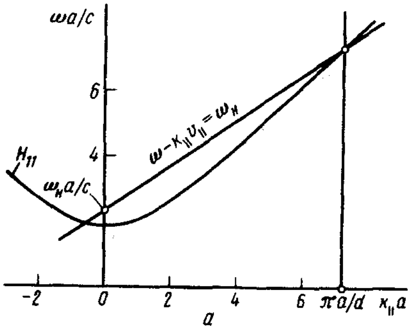


FIG. 1. Magnetic system and the free-electron maser resonator.

the bounce frequency $\Omega = \Omega_b = 2\pi v_\parallel / D$ in a periodic magnetic field (D is the period of the field), however, have heretofore been used as oscillators in most experiments. The corresponding type of FEM and FEL, ubitrons, are indeed very promising for extension to the optical and possibly also to shorter wavelength ranges. As far as the relative wavelengths are concerned, here the most attractive maser is based on the cyclotron autoresonance (CARM),[5] where the electrons, which rotate with frequency $\Omega = \omega_H = eH_0/mc\gamma$ in a uniform magnetic field $\mathbf{H}_0$, interact with a wave whose phase velocity $\omega/k_\parallel$ is close to the velocity of light. Under such conditions, close to the autoresonance,[6] the deviations of the particles from synchronism with the wave, caused by a change in their energies and translational velocities, almost completely compensate each other: $\Delta\omega_H \simeq -\Delta(k_\parallel v_\parallel)$. Because of this, CARM theoretically must have a higher efficiency and be less sensitive (adaptive) to the initial spread in electron velocities than other FEM and FEL.

In order to verify this, using a nonlinear theory,[5] we calculated a design (Fig. 1), in which, by changing the parameters of the accelerator and the electron-optical system, it would be possible to realize both the ubitron regime and the CARM regime (Fig. 2). The tubular electron beam has a diameter 6 mm, particle energy 350-600 keV, current 0.4-1.0 kA, and duration 100 ns. In order to decrease the spread in the transverse particle velocities $\Delta\beta_{\perp 0}$ and the radii of their leading centers Δr_0, we used a double cathode, placed in a magnetic field of the same magnitude as in the interaction section. Impressions on targets and photographs of the luminescence of metallized Dacron films, bombarded by the diffracted beam (using the procedure in Ref. 7), indicate that $\Delta r_0 \lesssim 0.5$ mm and $\Delta\beta_{\perp 0} \lesssim 0.05$.

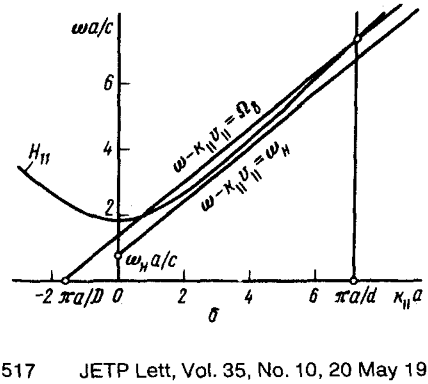
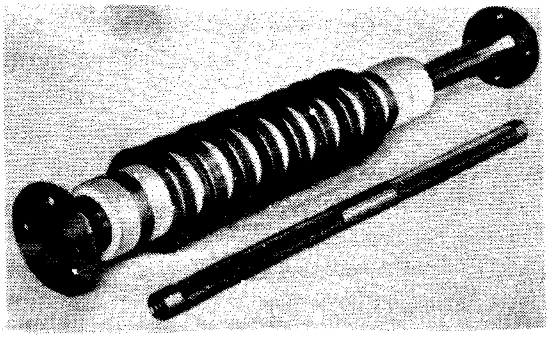


FIG. 2. Brillouin diagram of the generator: a) CARM regime ($\Omega_b < \omega_H$); b) ubitron regime ($\omega_H < \Omega_b$).



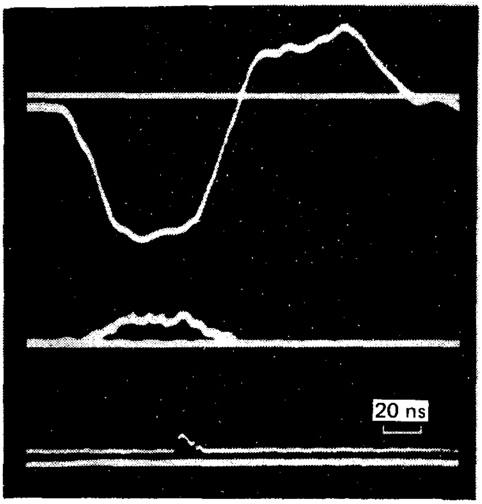


FIG. 3. Oscilloscope traces of the voltage, current, and microwave radiation.

Oscillatory energy was pumped into the beam by a spatially modulated magnetic field with $D = 2$ cm. Modulation was achieved by displacing the field of a pulsed solenoid by a system of copper rings with radial cuts (Fig. 1). The advantage of this construction over the widely used system of continuous rings is that it does not lead to a decrease in the longitudinal field. Three rings were used in the CARM and twelve rings in the ubitron.

The FEM resonator consisted of a segment of a cylindrical wave guide with a circular cross section with two Bragg mirrors: periodically corrugated sections, separated by a smooth section. The working wave was chosen as the wave H_{11} with phase velocity 0.97 c; the coefficient of reflection of the wave from the corrugated sections was 0.9. The radiation was extracted by a diffraction method.

The radiation frequency was determined by band-pass filters. The mode was identified by diagrammatic and polarization measurements. The power was measured by semiconducting sensors on the hot carriers, on which the radiation was incident along the calibrated channel formed by the output wave guide, a receiving horn, and a wave guide section with cross section 3.6 × 1.8 mm.

A well reproducible single-mode generation on the mode $H_{1,1}$ with wavelength 4.3 mm was obtained in the experiment. A power of 6 MW and an efficiency of 4% (taking into account losses in the resonator walls, an electron efficiency of 6%) was achieved in the CARM regime; the frequency transformation constituted $\omega/\omega_H = 3 - 4$. In the ubitron regime, a power of 2 MW and an efficiency of 1% were achieved; the frequency transformation was $\omega/\Omega_b = 5$. The radiation pulses had a duration of 5-30 ns (Fig. 3). When the resonator was replaced by a segment of a smooth tube with the same dimensions, there was no radiation within the limits of accuracy of the measurements, i.e., it was at least two orders of magnitude less intense than with the resonator.

The experiments performed by us, together with the theoretical representations, indicate the promise of high-current FEM with Bragg resonators and the advantages of CARM over a ubitron in the millimeter range and in the long-wavelength part of the submillimeter range.

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