Orotron oscillators and frequency multipliers as sources of coherent terahertz radiation

A.E. Fedotov[1], V.L. Bratman[1], B.S. Dumesh[2], P.B. Makhalov[1], F.S. Rusin[3]
[1]Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia
[2]Institute of Spectroscopy of Russian Academy of Sciences, Troitsk, Russia
[3]FGUP "VNIIFTRI", Mendeleevo, Russia

Abstract: **The orotron (the Smith-Purcell electron microwave tube with open cavity) provides coherent radiation at the frequencies up to 0.4 THz. The output power of 50-100 mW is obtained in the microsecond pulses with possibility of a wide frequency tuning. A proposed new scheme of a frequency-multiplication regime allows increasing the orotron operating frequency up to 0.6 THz.**

I. LOW-VOLTAGE OROTRONS

The frequency range 0.1-1 THz is very attractive for a number of research and technical applications including spectroscopy, diagnostics of various media, communications, etc. Nowadays the electron vacuum tubes such as a backward-wave oscillators (BWOs) [1] and gyrotrons [2,3] operate at the frequencies up to 1.3 THz with milliwatt and kilowatt power level, respectively. However, for some applications the radiation sources with the intermediate power level are needed. For conventional vacuum tubes based on the stimulated Cherenkov and transition radiation, such as BWOs, TWTs and klystrons, the main difficulty which limits the output power at short waves is a dramatic decreasing of the transverse size of the interaction region while the frequency increases. Small sizes lead to decrease of the electron current and output power. The transverse size of the interaction region can not be significantly increased due to of severe mode competition, which can not be avoided in the devices with closed electrodynamical systems. As in lasers and in vacuum tubes based on the Bremsstrahlung radiation (gyrotrons and free electron lasers), this difficulty can be avoided by use of open electrodynamical systems. As for slow-waves devices, this method is used in the orotron, or diffraction radiation generator (DRG) [4-6].

The two-mirror open cavity, which is used in orotrons, provides effective selection of transverse modes and allows significant increase of the transverse dimensions of interaction region and the electron current. Therefore, the orotrons and DRGs provide higher output microwave power as compared with backward wave oscillators (BWOs) [4], the most spread electron oscillators at submillimeter waves. Another advantage of the orotron is the high cavity Q-factor that ensures high stability of the frequency. At the same time, the high Q-factor results in a narrow band of electronic frequency tuning.

In the Institute of Applied Physics RAS in collaboration with VNIIFTRI, the Institute of Spectroscopy RAS, and GYCOM Ltd., the low-voltage pulse orotron oscillators with enhanced power have been developed in recent years [7]. In such a device (Fig. 1), a smooth concave mirror and a flat mirror with periodic structure form the two-mirror cavity. The multiple-pin periodic structures with periods of 80-170 μm, pin thickness of 15-40 μm and pin height of 500-800 μm are basically used. The structures with dimensions $10 \times 16\ \text{mm}^2$ are manufactured using the electric discharge machining. The operating orotron voltage and current are 500-5000 V and 50-400 mA, respectively, at pulse duration from 50 ns up to 10 ms. Thermionic cathodes produce the high-density electron beams with transverse dimensions of $3 \times 0.3\ \text{mm}^2$. For beam transportation inside the multiple-pin periodic structure, a NdFeB permanent magnet system providing uniform magnetic field of 1.25 T is used. The microwave power radiates from the cavity through the slots in the concave mirror into oversized rectangular waveguide.

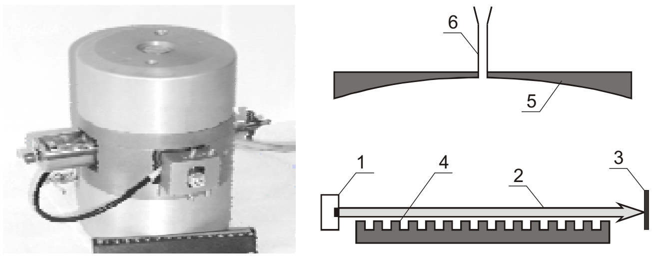

Fig. 1. Photo and a scheme of an orotron (1 – cathode, 2 – electron beam, 3 – collector, 4 – periodic structure, 5 – concave mirror, 6 – output waveguide).

The parameters of the developed orotrons are listed in the Table 1. In the experiments with the millimeter-wave orotron with 120 μm structure period the radiation with the frequency 140-300 GHz was detected at the voltage up to 3700 V. The maximal output power up to several hundreds milliwatts was obtained at the frequency about 200 GHz.

The submillimeter-wave orotron was designed for the frequency 360 GHz. In this device, the period of the structure was 100 μm. The output radiation in the frequency range 260-370 GHz was obtained; at the frequency 360 GHz the output power of 50 mW was measured with the frequency stability 10^{-7}.

More powerful millimeter-wave device was realized with the 170 μm structure period. For this oscillator, the output power up to 1 W was measured at the frequency 180 GHz in the microsecond pulses, and the power up to 600 mW was obtained at the frequencies up to 160 GHz in the millisecond pulses. The

9781-4244-3849-5/09/$25.00 ©2009 IEEE

possibility of the CW operation at the frequency 120 GHz with the power 200 mW was also demonstrated.

The orotron with 140 μm structure period provides the pulse power of 500 and 200 mW at the frequencies 180 and 260 GHz, respectively.

In the 2008-2009, a new orotron with the short-period structure (82 μm) was manufactured and tested in the microsecond-pulse regime. In this device, the frequency of 400 GHz is obtained which is now the highest frequency for the orotrons and diffraction radiation generators. The wide band of mechanical frequency tuning was observed in this oscillator. The estimated value of the output power at the frequencies 350-400 GHz is up to 50 mW; the power was limited by competition of the operating orotron mode with the parasitic surface modes. The further increase of the operating frequency can be obtained by using structures with shorter periods that requires an improved fabrication technology. The structure with period of 50-60 μm can allow the orotron operation at the 0.5-0.6 THz.

TABLE 1.
PARAMETERS OF DEVELOPED OROTRONS

Structure period (μm)	170	140	120	100	90	82
Frequency (GHz)	90-190	90-300	140-300	260-370	220-355	170-400
Power (mW)	1000-100	500-100	500-50	70-30	50-100	50

II. Frequency multiplication in orotrons

For further advancement of the orotron into the submillimeter wavelength range, a new regime of frequency multiplication is proposed [8]. In this regime, an orotron periodic structure serves simultaneously as a resonator for the low-frequency surface waves. These slow evanescent waves (the eigenwaves of the structure) are similar to surface plasmon waves in the meta-materials. In the proposed scheme, the π-type slow wave can be excited by synchronous electron beam (Fig. 2).

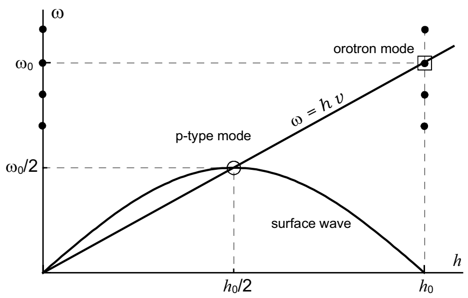

Fig. 3. Dispersion of the surface and volume modes in orotron for the regime of frequency multiplication.

If the frequency of the orotron mode is two times higher than that of surface π-mode, then the synchronism of the electrons with the operating orotron mode takes place simultaneously. Therefore, the orotron mode can be excited due to bunching of the electron beam in the field of the surface mode at the second harmonic of its frequency. It is important that in many cases the starting current of the surface mode is significantly lower than the starting current of the orotron excitation. Therefore, one can hope that the described regime allows generation at higher frequencies. An advantage of the proposed scheme of frequency multiplication is a possibility of frequency tuning for an orotron mode by moving the concave mirror. It allows providing the exact resonance between the high-frequency wave and the second harmonic of the low-frequency wave.

The low-voltage variant of the frequency multiplier with multiple-pin structure is studied numerically. According to simulations, at the operating frequency of 0.5-0.6 THz the output power of 50-100 mW can be provided by such a device.

In the studied frequency multiplier, the wide electron beam is reasonably to be used. Therefore, the problem of the transverse synchronization of the surface waves excited by different transverse parts of the electron beam is arising. According to simulations, the single-frequency and single-mode regime can be established due to transverse diffraction of the surface wave and due to synchronizing effect of the second-harmonic radiation accumulated in the open cavity [9].

A similar regime of frequency multiplication was observed earlier in the experiment with relativistic orotron. In this device, a conventional quasi-flat construction of the two-mirror cavity was used. In the experiment, a sheet electron beam with particle energy 400-450 keV, current 100-500 A and current pulse duration of 20 ns was formed using explosive emission cathode. In some regimes, simultaneous powerful radiation at both the frequencies of operating orotron mode (160 GHz) and of the parasitic surface π-mode (80 GHz) was observed.

In conclusion, the low-voltage pulse orotron generators of the short millimeter and long submillimeter waves with the operating frequency up to 400 GHz have been developed. The new method of frequency multiplication is proposed.

The work was supported by Russian Foundation for Basic Research under grants Nos. 09-02-00637, and 07-02-01158.

References

1. M.B. Golant, Z.T. Alekseenko, Z.S. Korotkova, "Wideband generators of submillimeter range", *Pribory i tekhnika eksperimenta*, No. 3, p. 231, 1969.
2. M.Yu. Glyavin, A.G. Luchinin, G. Yu. Golubiatnikov, "Generation of 1.5-kW, 1-THz Coherent Radiation from a Gyrotron with a Pulsed Magnetic Field", *Phys. Rev. Lett*., v. 100, No. 1, Art. 015101, 2008.
3. V.L. Bratman, Yu.K. Kalynov, and V.N. Manuilov, "Large-orbit gyrotron operation in the Terahertz frequency range", *Phys. Rev. Lett.* V. 102, No.24, Art. 245101, 2009.
4. F.S. Rusin, G.D. Bogomolov, "Orotron – an electronic oscillator with open resonator and reflecting grating", *Proc. IEEE,* v. 57, No. 4, p. 720, 1969.
5. V.P. Shestopalov, ed., "Diffraction radiation generators" (in Russian), Kiev: Naukova Dumka, 1991.
6. K. Mizuno, S. Ono, and Y. Shibata, "Two different mode interaction in electron tube with a Fabry-Perot resonator – the ledatron", *IEEE Trans. Electron Dev.*, v. 20, No. 8, p. 749, 1973.
7. V.L. Bratman, V.A. Gintsburg, et al., "Pulse wideband orotrons of millimeter and submillimeter waves", *Radiophys. Quantum Electron.*, v. 49, No. 11, p. 866, 2006.
8. V.L. Bratman, A.E. Fedotov, I.M. Khaimovich, P.B. Makhalov, "Excitation of orotron oscillations at the double frequency of the surface wave", *Radiophys. Quantum Electron.*, v. 50, No. 10-11, p. 780, 2007.
9. V.L. Bratman, A.E. Fedotov, P.B. Makhalov, F.S. Rusin, "Pulse wideband orotrons of millimeter and submillimeter waves", *Appl. Phys. Lett.*, v. 49, No. 11, p. 866, 2006.