УДК 537.862/621.385.69

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# SHORT-WAVE OROTRONS AND ORO-MULTIPLIERS *

The capabilities of two types of terahertz sources based on stimulated Smith – Purcell radiation of electrons in open cavities are discussed. A series of developed pulsed orotrons provides coherent radiation at frequencies up to 410 GHz with an output power of 1–0.1 W with high frequency stability. A promising alternative source with smaller currents than in orotrons is a frequency multiplier based on the excitation of a surface wave of a periodic structure and Smith – Purcell radiation of arising electron bunches inside the orotron cavity. A possibility of frequency doubling inside the orotron cavity is experimentally demonstrated at a frequency of 190 GHz.

*Keywords*: terahertz radiation, orotron, open cavity, slow-wave structure, surface wave, frequency multiplication.

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## КОРОТКОВОЛНОВЫЕ ОРОТРОНЫ И ОРО-УМНОЖИТЕЛИ

Обсуждается потенциал двух типов терагерцовых источников, использующих стимулированное излучение Смита – Парселла в открытых резонаторах. Серия разработанных импульсных оротронов обеспечивает когерентное излучение при частотах до 410 ГГц с выходной мощностью 1–0,1 Вт при высокой стабильности частоты. Перспективный альтернативный источник с токами меньшими, чем в оротронах, – это умножитель частоты, работа которого основывается на возбуждении поверхностной волны периодической структуры и излучении Смита – Парселла возникающих сгустков электронов в резонаторе оротрона. Экспериментально показана возможность повысить частоту в два раза внутри резонатора оротрона при частоте 190 ГГц.

*Ключевые слова*: терагерцевое излучение, оротрон, открытый резонатор, замедляющая система, поверхностная волна, умножение частоты.

## Introduction

The terahertz frequency range (0.1–10 THz) is very attractive for a number of research and technical applications. Nowadays electron sources of radiation such as backward-wave oscillators and gyrotrons can operate at frequencies up to 1.4 THz with milliwatt and kilowatt output power levels, respectively. However, sources with an intermediate power level of 0.1–10 W are much on demand in a number of spectroscopic applications. For conventional slow-wave tubes based on the stimulated Cherenkov and transition radiation (BWOs, TWTs, klystrons, etc.), the main difficulty limiting the output power at high

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[*] This work was supported by the Russian Foundation for Basic Research (project Nos. 09-02-00637 and 07-02-01158), and by the Presidium of the Russian Academy of Sciences (Program «Problems of physical electronics, charged particle beams and generation of electromagnetic radiation in high-power systems»).

frequencies is the dramatic decrease in the transverse sizes of the interaction region which leads to a decrease in the operating electron currents and, correspondingly, output power. In devices with closed electrodynamical systems, the transverse size cannot be increased due to mode competition. Using the open cavities in orotrons, or diffraction radiation generators [1; 2] can mitigate this problem. Operation of these oscillators is based on the stimulated Smith – Purcell radiation of a rectilinear electron beam moving near a grating mounted inside a two-mirror cavity.

The submillimeter radiation in orotrons was obtained in 1970 at a wavelength of 0.83 mm [3]. However, since the 1970s, there was no progress in the frequency increase. In the last decade, the demand for compact terahertz radiation sources has made the idea of the devices based on the Smith-Purcell radiation in an open cavity quite attractive again. In recent years our group has developed a series of relatively powerful and high-frequency pulsed orotrons [4; 5].

The orotron-like version of frequency multipliers (oro-multiplier) also seems an attractive device for frequency enhancement. This capability can be based on the excitation of a surface eigenwave of a periodic structure for bunching of electron beam [6]. The arising bunches can produce coherent radiation at the temporal harmonics of the surface wave frequency. This scheme has been intensively studied after recent experiments [7]. Its realization inside the orotron cavity [5; 8; 9] could provide stimulated and coherent character of the radiation.

## High-frequency orotrons

Stimulated Smith – Purcell radiation in an orotron occurs inside the two-mirror open cavity. The periodic structure located on the surface of the plane mirror produces slow spatial harmonic of the cavity field, which is in the Cherenkov synchronism with electrons. As in other non-relativistic slow-wave devices, the amplitude of the synchronous harmonic decreases with the distance from the structure surface. Correspondingly, for comb structures with short periods, only a thin layer of electrons moving close to the structure can efficiently interact with the high-frequency field. Therefore, for high-frequency orotrons it is attractive to utilize more complicated multi-pin periodic structures [4; 5]. The electrons move inside such a structure, so each longitudinal row operates as a periodic structure surrounded by a thin layer of electrons moving in a relatively strong field of a slow wave. This allows obtaining the required electron current using cathodes with lower density of emission in comparison with the devices of comb-type structure. This is very important at high frequencies since the starting current density of the orotrons increases drastically with the operating frequency.

The high-frequency orotrons developed [4; 5] have a common design and overlap a frequency range of 90-410 GHz (see table) at a low operating voltage of up to 5 kV. A cavity is formed by a smooth concave mirror and a flat mirror containing multi-pin structures with a longitudinal period of 80–170 μm. The operating current is 50–400 mA in pulses with a duration of 50 ns to 10 ms. The employed thermionic cathodes produce high-density electron beams with transverse dimensions of $3 \times 0.3$ mm$^2$. A NdFeB permanent magnet system with a uniform field of 1.25 T is used for beam transportation inside the pin structure. The output power radiates from the cavity through the slots in the concave mirror into a standard oversized (4-mm) rectangular waveguide. A 50-$\mu$m glass film is used as a vacuum window.

For a device with a long-period (170 μm) structure the possibility of CW operation at a frequency of 120 GHz with 200-mW power

| Structure period (μm) | 170 | 140 | 120 | 100 | 90 | 82 |
|---|---|---|---|---|---|---|
| Frequency (GHz) | 90–190 | 90–300 | 140–300 | 260–370 | 220–355 | 140–410 |
| Power (mW) | 1000–100 | 500–100 | 500–50 | 70–30 | 100–50 | 50–200 |

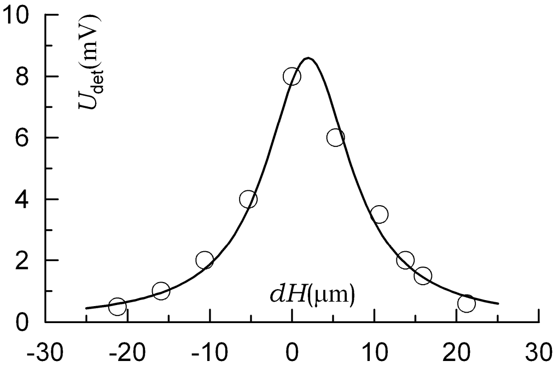
was also demonstrated. All the oscillators demonstrate a high short-time frequency stability of $10^{-7}$ due to using a high-Q cavity and a stable power supply.

An orotron with a short-period structure (82 μm) has recently been manufactured and tested in the microsecond-pulse regime. A frequency of 410 GHz, which is now the highest frequency for the low-voltage orotrons and diffraction radiation generators, was obtained in this device. The band of mechanical frequency tuning in this oscillator is close to 1.5 octaves. For a fixed distance between the cavity mirrors, the $\mathrm{TEM}_{00n}$ and $\mathrm{TEM}_{01n}$ open-cavity modes with high axial index $n = 25$–$52$ were observed. The power was measured by comparing signals from a semiconductor detector powered with the studied orotron and a terahertz BWO with known power. The output power at frequencies of 300 to 350 GHz is 100–200 mW.

## Orotron-based frequency multiplier

Frequency multiplication inside an orotron can be considered as an alternative method to increase the frequency. In the proposed regime, the orotron periodic structure serves simultaneously as a cavity for low-frequency surface (evanescent) waves. The operating surface wave bunches the electron beam at its frequency as well as at the frequency harmonics, and then the coherent electron bunches effectively excite the orotron mode at the harmonic of the surface wave frequency.

In contrast to papers where the open grating is considered as an electrodynamical system of such multipliers [6], we propose to use for such a device a two-mirror open cavity similar to the orotron one, which provides effective feedback for a definite frequency harmonic [8; 9]. In the realized scheme, the open-cavity mode operates at the second harmonic of the π-type surface mode frequency. Since the energy stored in the surface mode is significantly less than the energy of the orotron mode, the starting current of a multiplier can be significantly lower than the orotron starting current. Hence, the multiplier can operate at high frequencies utilizing the moderate current, when the direct orotron operation is complicated by the requirement of high current density.



Measured detector signal at a frequency of 190 GHz vs. the position of the orotron mirror (circles). The theoretical Lorentz line is also drawn

The experimental study of the orotron operation at the second harmonic of the surface wave was carried out on a base of the device with a periodic multi-pin structure with a period of 170 micrometers and height of pins of 0.7 mm. For a predicted value of voltage (3 kV), the radiation at the frequency of a surface pi-mode of 95.6 GHz, as well as excitation of a mode of the open cavity at a double frequency of 191.2 GHz, were simultaneously registered. The operating current (25–80 mA) was significantly lower than the orotron starting current (about 100 mA). In accordance with the theory, the multiplied radiation was measured in very narrow ranges of the position of the concave (moved) mirror (see figure), when the frequency of the open-cavity mode was equal to the doubled frequency of the surface wave. Precise frequency measurements using the spectrum analyzer prove that in the multiplier regime the frequencies are divisible, and the high frequency do not depend on the distance between the cavity mirrors. The dependence of the output power of the high-frequency wave on the electron current was close to the squared relationship. Thus, the multiplier nature of the high-frequency radiation is demonstrated, when the open-cavity mode is excited by a bunched electron beam (unlike the self-excitation in an orotron). The measured output power was about 1 mW for a current of 40 mA and several mW for 80 mA. At a higher current, a selective orotron generation with a frequency of about of 190 GHz was observed.

## Summary

Operated at low voltage and not requiring a strong magnetic field, the developed pulsed orotrons are compact and convenient radiation sources for a number of spectroscopy and diagnostics applications at frequencies of up to 410 GHz with a very broad band of electromechanical frequency tuning and high frequency stability. A promising slow-wave microwave oscillator based on a novel scheme of frequency multiplication in an orotron is successfully realized in the demonstrational experiment at a frequency of 190 GHz.

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*09.09.2010*