THE POSSIBILITY OF EFFICIENT SUB-TERAHERTZ SECOND-HARMONIC GENERATION IN LOW-VOLTAGE GYROTRONS

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A number of theoretical works predicts high values of the electronic efficiency for sub-terahertz gyrotrons operating at cyclotron harmonics even at low operating voltages. However, the achievement of an acceptable output radiation power by such devices faces significant difficulties associated with mode competition, creation of an electron beam with a relatively large current, high ohmic losses in walls and manufacturing cavities with the necessary accuracy. To solve these problems, the variants of low-voltage gyrotrons with a conventional cavity and a recently proposed version of a sectioned cavity are analyzed in detail, and the calculation of the electron-optical system for them is given. It is shown that when the micron precision of manufacturing cavities is achieved, it is possible to obtain output efficiency values of up to 5% and power up to 100 W at frequencies of about 0.4 THz and higher at the second cyclotron harmonic with a low operating voltage of 5 kV.

1. INTRODUCTION

CW sub-terahertz sources with a radiation power of the order of (1-100) W are very much in demand for spectroscopy and diagnostics of various media [1, 2]. In gyrotrons, this relatively high power can be obtained even at low voltages down to (1-5) kV [3-5]. The decrease in voltage not only makes the device more compact, but also simplifies the selective excitation of the operating mode in an over-sized gyrotron cavity and reduces the gyrotron sensitivity to the particle velocity spread, which enables to operate in high longitudinal modes and obtain a broadband frequency tuning. In this paper, we study the possibilities of second-cyclotron-harmonic operation in gyrotrons with both a conventional cavity and a sectioned cavity with a widening (step) in the middle part [6-8]. The increase in the radiation power in the sectioned cavity can be ensured by a significant reducing the ohmic losses in the walls.

At low voltages, the relativistic non-isochronity of particle rotation in gyrotrons is small, and therefore, a change in their rotational energy leads to a relatively small change in the cyclotron frequency. Under such conditions, phase bunching of particles and efficient radiation of bunches can be ensured by increasing the number of cyclotron rotations of particles during their passage through the cavity. It can be satisfied if the parameter of the inertial particles bunching $\mu = \pi\left(\beta_{\perp 0}^2/\beta_{\parallel 0}\right)\left(L/\lambda\right)$ is sufficiently large, where $\beta_{\perp 0}$, $\beta_{\parallel 0}$ are the initial values of the electron transverse and longitudinal velocities normalized to the speed of light, L is the length of the interaction space of electrons with the wave, $\lambda = 2\pi c/\omega$ is the wavelength. If a longitudinal field structure is close to the Gaussian distribution and to the field in a conventional gyrotron cavity, $\mu_{opt} \sim 20$ for the second harmonic [9]. To obtain the necessary output power at low voltages, an electron beam with a comparably large current and a small spread of electrons is necessary. Because of space-charge effects, the translational velocity of particles in such a beam cannot be much less than their rotational velocity: $\beta_{\parallel 0} : \beta_{\perp 0}$. Therefore, for a voltage of the order of 5 kV, the optimum length of the cavity is very large: $L : (30-50)\lambda$.

The decrease in the gyrotron voltage leads to a reduction in the achievable electron current and the need to use long cavities for the possibility of effective operation at cyclotron harmonics. A conventional cavity in the form of a piece of a cylindrical waveguide bounded by a cutoff narrowing at the cathode end and a widening for diffraction radiation output at the collector end has a high "useful" diffraction Q-factor (Q_d) which often significantly exceeds the Ohmic Q-factor (Q_{ohm}) already in the short-wave part of the millimeter range. With a length $L=\left(30-50\right)\lambda$, at which the gyrotron starting current can be exceeded at low voltage and the parameter μ is close to optimum, the mode frequency is very close to the cut-off for the cylindrical part of the cavity. Correspondingly, the group velocity of the waves forming the mode field is very small compared with the speed of light, and the coefficient of reflection from the open collector end is very close to unity even at a small inhomogeneity of the cavity profile. Therefore, even at small angles of the widening in the output conic section, the Q_d is very large: $Q_d > 5\cdot 10^4$. At the same time, the Q_{ohm} of the TE_{mp} mode of a conventional cylindrical cavity, as a rule, does not exceed the value Q_{ohm}~10^4 for the frequency range of interest $f \geq 0.2$ THz. Under these conditions, only a small part of the power radiated by electrons is derived from the gyrotron.

2. GYROTRONS WITH CONVENTIONAL CAVITIES

Let us analyze a concrete example of a gyrotron at the second harmonic with a conventional cavity. According to [4], an efficient generation with a frequency of 395 GHz is, in principle, possible in this case even at a voltage 5 kV and lower; the used values of the current and pitch-factor are 0, 5 A and 1.4, respectively. The mode $TE_{1.6}$ is considered as the operating one, the length of the cylindrical part of the cavity is 25 mm, input and output cone angles are 3° , and Q_{Ohmic} = 10,000. The radius of leading particle centers $R_e = 0,22\,mm$ ensures maximum of the interaction of electrons with the operating mode. A more detailed analysis shows, however, that it is difficult to realize generation on the $TE_{1,6}$ mode because of the danger of parasitic excitation in the gyro-BWO regime on the fundamental resonance with the travelling wave $TE_{1,3}$ and also because of problem in creation of an electron beam with a small injection radius. In this situation, it is possible to provide only a much lower power than was predicted in [4].

[1] Consider another operating $TE_{6.2}$ mode in the gyrotron with the same cavity, voltage and current. In this case, the starting conditions are also fulfilled for the parasitic fundamental-resonance $TE_{1.2}$ mode in the gyro-BWO regime (
Fig. 1a). However, if the
excess over the threshold is large for the operating mode and small for the parasitic one, and, hence, it is possible to expect a stable generation at the second-harmonic mode [6]. A much larger optimal radius of the leading center for this mode makes it possible to obtain an electron beam with parameters of 5 kV / 0.5 A / g=1.4 and a velocity spread of less than 20%. Such a beam can selectively excite a conventional

cavity with the above parameters. However, because of the too high diffraction and low Ohmic Q- factors, Q_d = 89,000 and Q_{ohm} = 5,800, the losses in the cavity walls are very large.

a) b)

Fig. 1. a) Starting currents for the second-harmonic $TE_{6,2}$ mode and parasitic fundamental-harmonic $TE_{1,2}$ mode; b) Output power (solid line) and efficiency (dashed line) for the low-voltage second-harmonic gyrotron with the operating $TE_{6,2}$ mode of the conventional cavity.

[2] Calculation of the gyrotron in the approximation of the non-fixed structure of the field, considering the influence of the electron beam on the frequency and longitudinal field structure, gives the efficiency 3.3% and power 83 W (Fig. 1b). According to calculation, the considered gyrotron is very critical to manufacturing inaccuracies: the permissible conicity of the cylindrical part of the cavity is only about 0.5 μm.

3. GYROTRONS WITH COUPLED CAVITIES

A prospective alternative to the conventional gyrotron cavities may be systems with two cavities coupled through a relatively wide waveguide, which were proposed for a radical reduction in ohmic losses in high-harmonic terahertz gyrotrons [7-9]. For the same total length, the Q_d of such a system can be many times less than in the conventional cavity [12, 7-11]. The longitudinal distribution of the fundamental mode has one or less arc of the sinusoid in the cavities, where the group velocity of the waves is small, and the sinusoid with a much shorter period in the wide middle part of the system, where the group velocity of the waves is many times larger. The wide part of the cavity makes a small contribution to the Q_d, which is determined mainly by the short cavity sections and can be much smaller than for a regular cavity of the same total length.

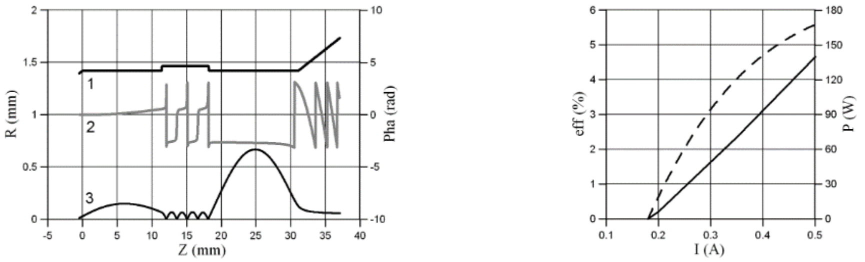
A gyrotron with coupled cavities (GCC) was previously studied for the millimeter wave range and the case of coupling through a narrow cutoff waveguide [12]. The GCC represents a gyro-klystron with feedback [12, 7], in which the field structure can be very favorable for a high electronic efficiency. The use of a sectioned cavity makes it possible to drastically reduce the share of ohmic losses and increase the gyrotron efficiency. In [7, 8, 10, 11], the case of a relatively large widening was studied, when there is a danger of parasitic generation and mode transformation. A simpler possibility of using a widening with a diameter jump of the waveguide many times smaller than the wavelength and these parasitic effects are less dangerous were considered in[9].

Let us consider a GCC on the second harmonic with the frequency of 395 GHz, operating voltage 5 kV, beam current 0.5 A, particle pitch-factor 1.4, radius of the leading centers $R_e = 0.64$ mm, a spread of transverse electron velocities of 20%, the operating TE_{62} mode with $Q_{ohm} = 5{,}800$. The longitudinal field structure and the Q_d of the modes in the GCC can vary over a wide range with a change in the ratio of the cavity lengths and the value of the widening. A change in the ratio of the lengths and / or radii of the cavities leads to a separation of their complex frequencies, and the change in the radius of the widening leads to a change in the reflection coefficients of the partial traveling waves and the coupling coefficient of the oscillations in the resonators. The change in the length of the widening also strongly affects the reflection of waves.

If an integer number of longitudinal half-waves is laid on this length, then in neglect of the wave transformation, the small widening is transparent for the normal wave. The wave amplitudes at the end of the first and the beginning of the second cavity are close to one another, and the field structure in the cavities is close to the spaced apart pieces of the cut structure of the cavity mode of the same total length with a high-frequency spatial filling between these pieces. If the length of the widening differs from the whole number of half-waves by a quarter of the wavelength, a strong reflection is possible, even from a small step. Then the amplitude of the oscillations at the end of the first and the beginning of the second cavity, and also within the widening, are small compared with the maximum of the field. For effective interaction of electrons with a field, it is expedient to use a distribution with amplitude in the first cavity several times smaller than the amplitude in the second cavity.

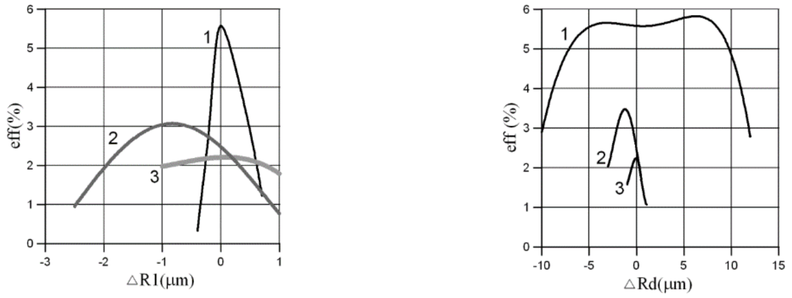
Based on these considerations, three following GCC variants with a large total length of the system providing excitation of oscillations at a current 0.5 A, favorable longitudinal field distributions and relatively low values of the Q_d as well as comparatively high efficiency and radiation power are found.

1. In a GCC with long and close cavities with lengths $L_1 = 11.4$ mm and $L_2 = 12.9$ mm (about 15λ and 17λ, respectively) and equal radii, a short coupling widening between them with $L_d = 6.8$ mm provides a favorite field structure of one of the normal waves (Fig. 2a). An increase of the efficiency and radiation power by almost two times in comparison with the conventional cavity takes place in this case due to the decrease in the Ohmic losses. At the total length $L = 31.1\lambda$ the cavity $Q_d = 14{,}000$ is much less than that $Q_d = 88{,}000$ for the conventional cavity of the same length, while the efficiency and power exceed 5% and 140 W, respectively (Fig. 2b). Because of the small separation of the partial cavity frequencies, this variant is very critical to the difference in the diameters of the cavities, which can be caused by the inaccuracy of manufacturing (Fig.3a). At the same time, it is of low criticality for the size of the short widening (Fig. 3b).



a) b)

Fig. 2. a) Profile of a sectioned system with long cavities coupled through a short widening (line 1), phase and amplitude HF longitudinal field distributions (lines 2, 3), b) efficiency (dashed line) and power (solid line) for the operating TE_{62} mode.



a) b)

Fig. 3. A change in the efficiency for the variants 1, 2, and 3 of the gyrotron with coupled cavities in dependence on the radius of: a) the first cavity and b) the widening.

2. A system with shorter cavities whose lengths differ significantly from each other: L_1 = 6.8 mm (9 λ), L_2 = 11.4 mm (15 λ), coupled through a long "transparent" widening with L_d = 16.5 mm (21.7 λ) (Fig. 4), has even lower diffraction Q, Q_d = 8,400, at a larger total length. The efficiency and power in this case are less than for the previous cavity: 2.5% and 62 W. However, due to the greater frequency separation, this system is less sensitive to the difference in the diameters of the cavities (Fig. 3a); at the same time, it is more critical to the magnitude of the radius of the widening (Fig. 3b).

The longitudinal field distribution in this cavity was also found by direct solution of the Maxwell equations using the CST Microwave Studio code. With a slight correction of the phase advance due to a drift (widening) reduction of 0.1 mm, a good agreement is obtained with the structure found from the irregular string equation in the approximation of a fixed field structure (Fig. 5). This calculation confirms that the transformation of the operating mode into modes with a different transverse structure is very small.

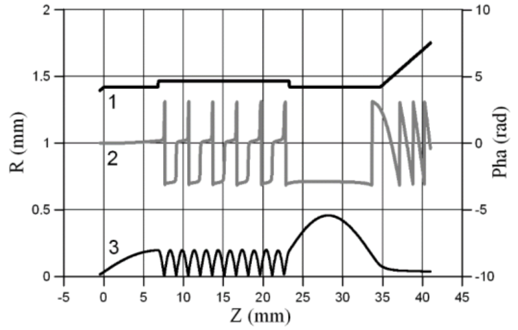
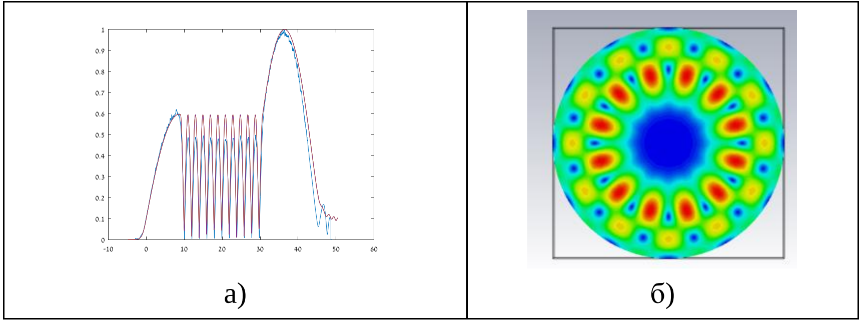


Fig. 4. Sectioned cavity (line 1) with short sections that are very different in length (L_1 = 6.8 mm, L_2 = 11.4 mm), coupled through a long widening (L_d = 16.5 mm), longitudinal phase (line 2) and amplitude (line 3) distributions of the HF field.

3. Even less sensitive to changes in the radius of the cavity is a system with a shorter first and a long second cavities (L_1 = 4.6 mm= 6 λ, L_2 = 13.7 mm= 18 λ) coupled through a "transparent" drift section (L_d = 22.5 mm) (Fig. 6a). With a large total length, this system (Fig. 6) has a relatively high Q_d=14,500 and low efficiency and power: 2.2% and 55 W. It has low criticality to the difference in the radii of the cavities and a strong criticality to the change in the radius of the widening (Fig. 3b).



а)　　б)

Fig. **5**. a) Comparison of longitudinal field distributions in a sectioned cavity, found from the irregular string equation (red line) and using the Microwave Studio code (blue line); b) transverse structure of the $TE_{6.2}$ mode.

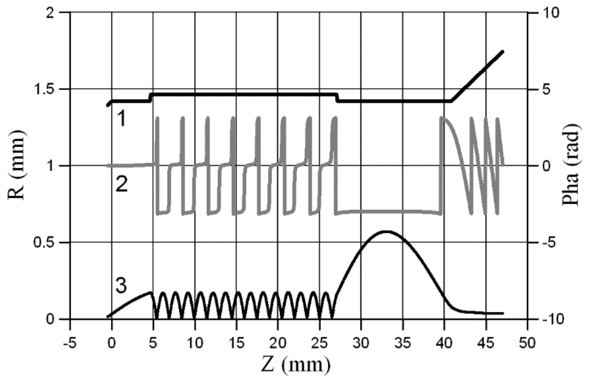


Fig. 6. Sectioned cavity with short first and long second cavities coupled through the wide waveguide section (1), phase (2) and amplitude (3) distributions of the HF field.

4. ELECTRON GUN

One of the factors that essentially limits the possibility of a significant reduction in the voltage of high-harmonic sub-terahertz gyrotrons is the problem of creation and transportation of poly-helical electron beams with a sufficient current and an acceptable spread of parameters. In particular, it is difficult to form the beams with a small radius of the leading centers in conventional magnetron-injection guns (MIGs). In this case, to obtain an above considered value of the electron current 0.5 A, a sufficiently large emitter is required, which leads to the need for strong beam compression. Then the velocity spread is basically defined by the values of initial electron velocities at the emitter. A negative factor for high compression is also the small value of the magnetic field at the cathode, which leads to the reduction of the electric field at the emitter. As a result, the effect of space-charge fields in the near-cathode region leads to a strong sensitivity of the gun relative to a change in current value or geometric parameters. Estimates show that for the second-harmonic gyrotron with a frequency of 395 GHz, a voltage of 5 kV and a pitch factor of 1.4, when the maximum interaction is encountered for modes with azimuthal indices 1 and 3 or 0 and 4, the radius of the leading centers is too small for a current of 0.5 A. That is why the $TE_{6.2}$ mode was chosen as the operating one. Using a code Angel-2DS [13] a two-electrode MIG was calculated for this mode that can form a laminar helical beam (Fig. 7 and Table 1) with a small velocity spread of about 10%.

Table 1. Parameters of gyrotron electron-optical system

Operating magnetic field	4,1 T
Voltage	5 kV
Beam radius in cavity	0.64 mm
Cavity radius	1.42 mm
Operating current	0.5 A
Pitch-factor	1.4
Electric field on cathode	8.5 kV/cm
Compression of magnetic field	30
Emitter's inclination to the axis	45°
Emitter radius	3.5 mm
Cathode-anode gap	7.5 mm
Emitter width	0.6 mm
Emission current density	3.8 A/cm^2
Spread of transverse velocities without taking into account the initial particle velocities	5%
Spread of transverse velocities caused by initial electron velocities	8%
Total spread of transverse velocities	10%

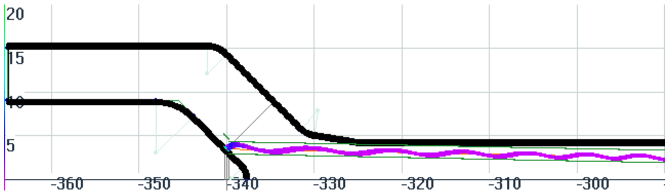


Fig. 7. Profile of the magnetron-injection gun and electron trajectory (dimensions are given in mm).

5. CONCLUSION

According to simulations, second-harmonic gyrotrons with a radiation frequency of about of 0.4 THz and higher and a low voltage of down to 5 kV can provide an output power level of the order of (10-100) W. In principle, this is possible with conventional cavities, but more efficient may be sectioned systems in the form of two cylindrical cavities coupled through a wider cylindrical waveguide. A gyrotron with such an electrodynamic system (GCC) is a gyro-klystron with feedback, in which it is possible to create a variety of longitudinal structures of normal modes having diffraction *Q* and ohmic losses many times smaller than in conventional cavities of the same total length. It should be noted that the creation of both types of electrodynamic systems with the necessary micron accuracy is a difficult technological task. It should be noted that the operability of a system of coupled cavities has already been demonstrated in experiments [10, 11] aimed at increasing the efficiency of a terahertz Large Orbit Gyrotron [14].

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