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Terahertz gyrotrons with quasi-regular cavities

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Abstract

We describe two ways of the use in high-harmonic gyrotrons of quasi-regular cavities with short irregularities formed by the widening of cavity radius. The first one is a significant improvement of the selectivity of the second-harmonic gyrotrons due to the supression of parasitic near-cutoff fundamental-harmonic waves. The second approach is aimed to solve a typical problem of weakly-relativistic high-harmonics gyrotrons, namely, the use of long cavities ensuring extremely high diffraction Q-factors and a great share of Ohmic losses. We propose a quasi-regular cavity with periodic phase correctors, where a far-from-cutoff axial mode with a decreased diffraction Q-factor is excited in a gyrotron-like regime.

1. Introduction

The gyrotron is widespread variety of electron cyclotron masers based on the selective excitation of anear-cutoff mode of an open microwave cavity by a beamof electrons rotation in a magnetostatic field. The principal advantages of the gyrotron are high mode selectivity achievedin simple microwave systems and weak sensitivity of the electron-wave interaction to velocity spread of electrons. Since the output frequency of the gyrotron is close to the electron cyclotron frequency or its harmonics (and istherefore proportional to the magnetic field intensity in thecavity), a natural way to decrease the operating magnetic fieldis the use of operation at the harmonics of the cyclotron frequency. However, there are well-known problems caused by the decreasing in intensity of electron-wave interaction with increasing operating harmonic number. At a fixed electron current, a longer operating cavity is required, in general, to provide the start of oscillations at a high cyclotron harmonic. In this situation, there is a risk of self-excitation of parasitic low-frequency modes at low cyclotron harmonics. Also increasing in cavity length leads to increasing in diffraction Q-factor and, therefore, Ohmic losses. Thus, a great share of the rf power extracted from the electrons beam is spent in the cavity wall. In this work, we propose relatively simple approaches based on the use a quasi-regular cavity aimed to solving the described problems.

2. Improvement of the mode selectivity of high-harmonic gyrotrons due to the weakening of the interaction of electrons with parasitic low-harmonic waves

The proposed method for improvement of the selectivity of the second-harmonic gyrotrons is based on the use of cavities with short irregularities (Fig. 1). Parameters of every irregularity are chosen so that the incursion of the phase of the operating second-harmonic wave in the corrector is equal to 2π and, therefore, such a corrector practically does not effect on the interaction of electrons with this wave. As for fundamental-harmonic near-cutoff parasitic waves, their phase incursions are twice smaller. Since the π-shift of the wave phase changes the “sign” of the electron-wave coupling, this lead to a significant degradation of the interaction of electrons with the parasitic waves (an increase in their starting currents).

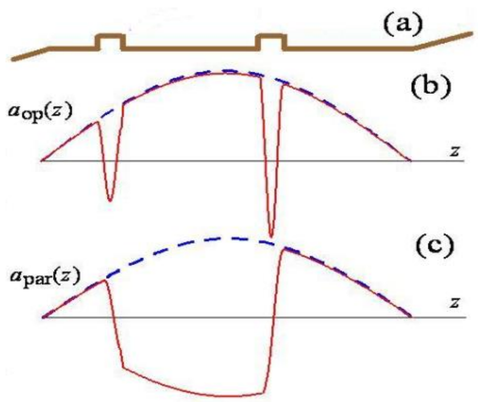

Figure 1. (a): Schematic of a quasi-regular gyrotron cavity including two short irregularities. (b) and (c): Transformation of axial structures of the second-harmonic operating gyrotron wave and of the fundamental-harmonic parasitic wave, respectively. Dashed/solid lines correspond to regular/irregular cavities, respectively.

According to analysis of a general model [1], the use of one phase corrector provides an increase in the starting current of the parasitic by a factor of 4-8, whereas the use of two irregularities may increase this starting current by a factor of 20-30. These statements are confirmed in a course of detailed simulations aimed to provide the selective second-harmonic operation in various gyrotrons. This approach was applied to relativistic (280 keV / 10-50 A) gyrotron operating at a frequency of 60 GHz at the second cyclotron harmonic. This oscillator is to be realized as a development of the previous experiment [2], where a fundamental-harmonic gyrotron operating at a frequency close to 30 GHz was realized. Possibilities for the frequency enhancement up to 60 GHz by transition to the second cyclotron harmonic are difficult due to problems of selectivity; namely, spurious excitation of the fundamental-harmonic waves should be avoided.The problem of the mode selection is solved by the use of a cavity having the same length and a one phase corrector. The existence of the selective element increases the starting current of the parasitic wave TE5,3 from 3-5 A up to 20-30 A with no significant change in the starting current of the operating wave TE13,4

3. Improvement of the mode selectivity of high-harmonic gyrotrons due to decreasing Q-factors of parasitic low-harmonic waves

Alternative method for improve the selectivity of excitation of the operating mode in quasi-regular cavity based on the reduction of the diffraction Q-factors of near-cutoff spurious modes due to its transformation into traveling waves. In this scheme (Fig. 2) operating cavity is the simplest case of quasi-regular system with one irregularity (widening of cavity radius), which is located in the middle of the cavity.

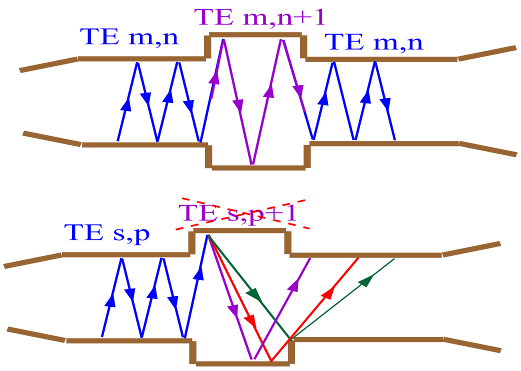

Figure 2. Illustration of selectiveproperties of cavity widening, which is resonant for operating near-cutoff wave (top) and non-resonant for spurious waves (below).

The radius of each regular part of the cavity corresponds to the cutoff radius of the operating $TE_{m,n}$ wave, and the radius of the widening corresponds to the cutoff $TE_{m,n+1}$ wave with the additional variation of the radius and with the same frequency. Thus, during the transition from the regular part to widening the operating near-cutoff $TE_{m,n}$ wave of gyrotron converted to near-cutoff $TE_{m,n+1}$ wave for the widening. Then, during the transition from widening to the regular part $TE_{m,n+1}$ wave transforms back to operating wave with insignificant losses. At the same time cavity widening does not have the same resonance properties for the parasitic near-cutoff waves excited at fundamental cyclotron resonance, and a significant share of the power of each of these waves is lost due to scattering to the travelling waves.

This approach is planned to apply for recently realized in IAP conventional gyrotron with tubular electron beam (50-70 keV, 15A) operating in terahertz frequency range (0.67 THz) with a relatively high power (about hundreds of kW) wherein the high transverse $TE_{31,8}$ mode excited at the fundamental cyclotron harmonic. The use of the proposed scheme makes it possible the transition to operation at the second harmonic of the cyclotron frequency, which could be a way to implement a gyrotron with record characteristics (output power about tens of kW on 1,3TGz).

4. Gyrotron-type excitation of far-from-cutoff waves in sectioned cavities

A typical problem of weakly-relativistic high-harmonic gyrotrons is the use of long cavities ensuring extremely high diffraction Q-factors for the operating near-cutoff waves and, therefore, with a great share of Ohmic losses [3-7]. We propose a relatively simple approach, which can reduce diffraction Q-factors in gyrotrons with a long operating cavity [8]. We propose to use a cavity consisting of several regular sections, which are separated by short non-regularities providing the π-shift of the wave phase between the sections (Fig. 3). Such a configuration ensures the "gyrotron-like regime" of the electron-wave interaction not for the lowest (near-cutoff) axial mode of the cavity, but for a far-from-cutoff mode possessing a relatively low diffraction Q-factor.

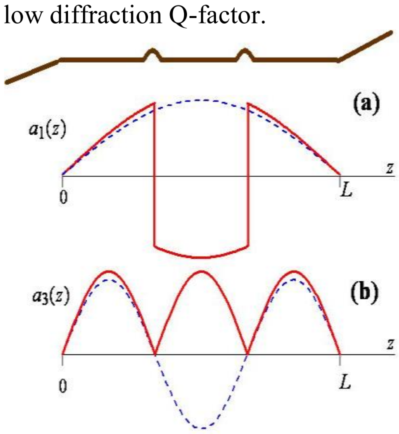

Figure 3. Two π-shift phase correctors split the cavity into three equal sections. (a): The lowest single-variation axial mode of the regular cavity (dashed line) is transformed into a wave with three-variation structure (solid line). (b): The three-variation axial structure of the third mode of the regular cavity (dashed line) is transformed into a gyrotron-like wave with constant sign (solid line).

Here, the "gyrotron-like regime" means that the far-from-cutoff wave is excited under the gyrotron-like cyclotron resonance condition; therefore, the sensitivity to the cyclotron velocity spread is weak, and the efficiency of the electron-wave interaction is relatively high. Figure 3 illustrates a partial case, when two correctors are placed at points, which coincide with two points of the change of the signs of the field of the third axial mode in the regular cavity. Therefore, two π-shift phase correctors transforms three-variation axial mode of the regular cavity into a gyrotron-like single-variation wave.

This approach is used to design operating cavities for pulsed (30 keV, 1A, 1.0-1.3 THz) and CW (30 keV, 1A, 0.38-0.50 THz) large-orbit gyrotrons operating at third and fourth cyclotron harmonics. The 0.5THz CW fourth-harmonic gyrotron requires a long (50 wavelengths) operating cavity, so that the diffraction Q-factor of the lowest axial mode (over 100,000) is much greater than the Ohmic Q-factor (~5,000), and the share of Ohmic losses exceed 95%. The use of a sectioned cavity (Fig. 4) makes possible to reduce the diffraction Q-factor of the operating wave down to ~30,000, and to reduce the share of Ohmic losses down to 85%; which corresponds to a threefold increase in the output wave efficiency. It is important, that the presence of the two irregularities does not lead to a considerable transformation of the operating wave $TE_{4,8}$ into the lower mode $TE_{4,7}$ (Fig. 4).

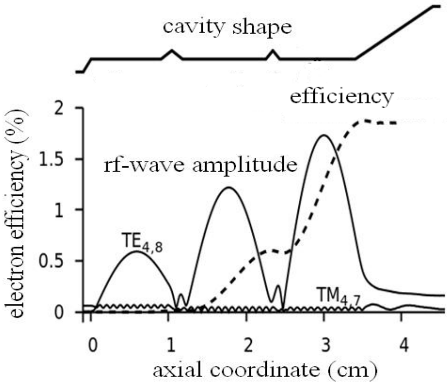

Figure 4. Large-orbit fourth-harmonic gyrotron: cavity shape, the electron efficiency versus the axial coordinate, the spatial rf-wave structure of the operating mode $TE_{4,8}$ corresponding to the third axial mode, and the spatial rf-wave structure of the mode $TE_{4,7}$ excited due to transformation of the operating wave $TE_{4,8}$ on the two irregularities.

4. Acknowledgements

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5. References

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