Complicated cavities for high-harmonic THz electron masers

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Abstract

To ensure high selectivity of excitation of the operating high-cyclotron-harmonic modes in gyrotrons, it was proposed to use resonators of complex shape with one or more longitudinal or transverse selective grooves. The use of cavities of this type can be the way to achieve stable single-mode gyrotron operation at frequencies of about 1 THz with a sufficiently high (several kW) output radiation power level.

1 Introduction

Advancement of the gyrotrons to the terahertz frequency range requires operation at the higher cyclotron harmonics. In the case of weakly-relativistic electron energies and moderate operating currents (which is typical for gyrotrons developed for applications and operating in long-pulse and CW regimes) this approach faces a dramatic weakening of the electron-wave coupling with increasing the harmonic number. This leads at least to the following two problems. The first one is a significant level of Ohmic losses. Long (tens wavelengths) cavities are required to excite a high-harmonic wave. The diffraction Q-factor of the near-cutoff operating wave increases rapidly with an increase in the ratio between the length of the cavity and the wavelength, whereas the Ohmic Q-factor is almost independent on the cavity length. Due to this fact, the Ohmic losses in the THz high-harmonic gyrotron can be as high as 80-90% of the power emitted from the operating electron beam [1-3]. Therefore, an important problem is the design of cavities providing a long length of the electron-wave interaction together with a decreased diffraction Q-factor of the operating wave.

The second problem is competition of the operating high-harmonic oscillation with waves excited at lower cyclotron harmonic. This problem is especially important in the THz frequency range, where the mode spectrum is dense due to the inevitable use of oversized cavities. Long cavity lengths of the high-harmonic gyrotrons exacerbate this problem. Therefore, the implementation of terahertz high-harmonic gyrotrons requires special electrodynamic selection methods.

We describe our works aimed at the use of cavities of complicated shapes in high-harmonic gyrotrons as a way to increase efficiencies of their operation at high cyclotron harmonics and to improve their selective properties. These works are mainly aimed at the implementation of the large-orbit gyrotrons (LOGs) developed at our Institute on the basis of two experimental installations [3]. At the same time, some approaches have proved attractive also for traditional gyrotron configurations [4].

2 Cavities with selective axial irregularities

A known approach is the use of cavities with axial inhomogeneities [5]. For a near-cutoff wave $TE_{m,p}$, any irregularity can lead to significant losses due to transformation of this wave into lower modes. In order to improve selectivity of excitation of a high-cyclotron-harmonic wave, one should propose an inhomogeneity which does not disturb the operating wave but provides significant losses for parasitic low-harmonic waves. In the case of coupled cavities (Fig. 1 a), their radii are chosen to support near-cutoff modes $TE_{m,p}$ and $TE_{m,p+1}$ at the same frequency (Fig. 1 b). As a result, one mode transforms into the other without loss. For any parasitic near-cutoff mode this inhomogeneity is not resonant and causes scattering.

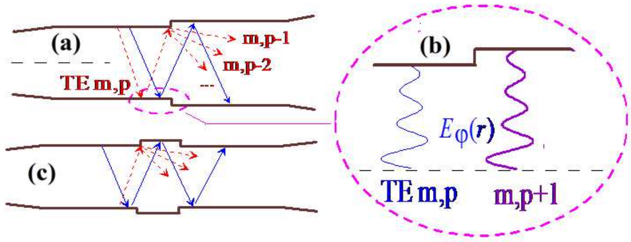

Figure 1. (a) Two-coupled-cavities gyrotron microwave system. (b) Operating and parasitic waves in the region of the axial inhomogeneity. (c) Cavity with a short selective element.

The problem of difficulty of providing resonant coupling of two high-Q cavities can be overcome by using a short resonant inhomogeneity working on the same principle (Fig. 1 c) [6,4]. Recently [4], this approach was used to realize a pulsed second-harmonic gyrotron operating in a high transverse mode ($TE_{58,13}$) at a frequency near 1.2 THz. At the moment, we together with our colleagues from Fukui University develop with approach in framework of realization of a 15 kV/0.5A/400 GHz frequency-tunable second-harmonic CW gyrotron.

We use this approach to design a quasy-regular cavity for the pulsed 1THz LOG developed for plasma applications. In the previous 80 kV/0.7 A experiment [1], the operating $TE_{3,7}$ mode was excited at the third cyclotron harmonic with a power of ~400 W. However, increasing the e-beam power makes it difficult to use this mode, because it is suppressed by the parasitic second-harmonic mode $TE_{2,5}$ (Fig. 2). According to multi-mode simulations, the introduction of an irregular element in the form of a short axially symmetric groove into the cylindrical part of the cavity provides the selective generation at the operating mode with the output power 5 kW.

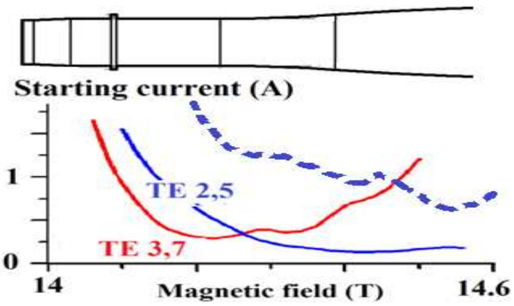

Figure 2. Quasi-regular cavity with a selective groove. Starting currents of the operating $TE_{3,7}$ and parasitic $TE_{2,5}$ modes versus the magnetic field (the dashed curve illustrates the effect of the selective groove to the parasitic wave).

3 Azimuthally-assymmentic cavities

A natural development of the approach described previously is to use resonant irregularities affecting the parasitic waves over the entire length of the cavity. This is possible in a cavity whose cross-section possesses azimuthal inhomogeneities occupying almost the entire cavity length. Their radial size is selected so that they minimally disturb the operating $TE_{m,p}$ mode rotating around the axis of the cavity. Since the radius of the groove corresponds to the near-cutoff $TE_{m,p+1}$ mode at the same frequency, the rotating $TE_{m,p}$ mode is transformed inside the groove into the $TE_{m,p+1}$ mode without stopping rotation and re-radiation into other modes (Fig. 3 a). In fact, the operating mode behaves like if it does not “feel” the groove. As for the parasitic modes (Fig. 1 b), the grooves provide negative effects on them.

Figure 4 illustrates our simulations aimed at providing selective third-cyclotron-harmonic $TE_{3,7}$-mode generation in the pulsed 100kV/1.2A/1THz LOG mentioned in Sect. II, From the point of view of the parasitic second-harmonic mode $TE_{2,5}$, the use of a cavity with two azimuthal inhomogeneities weaken the electron-wave coupling due to stopping rotation of this wave, disturbs its transverse structure, increase Ohmic losses, and shifts its eigenfrequnecy. As a result, CST simulations predict single-mode operation of the third-harmonic wave. According to these simulations, the presence of the two azimuthal inhomogeneities practically does not affect on the excitation of the operating third-harmonic wave.

In our simulations, we get a set of stationary polarized transverse modes of the azimuthally-asymmetric cavity. The electron beam in the gyrotron effectively interacts with the rotating wave. This wave is formed by two orthogonal waves of stationary polarization. In the CST simulations, we find the eigenfrequencies of these two waves. The introduction of the grooves leads to appearance of a difference in these frequencies, Δf. When it exceeds the cavity resonance band, f/Q, the rotating wave is transformed into two different waves with stationary polarizations.

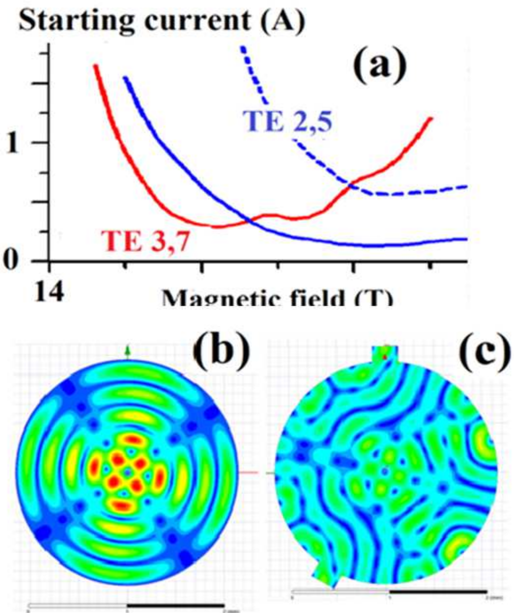

Figure 3. (a): Starting currents of the operating TE3,7 and the parasitic TE2,5 waves versus the magnetic field in the azimuthally-symmetric cavity (solid curves) and asymmetric cavity (dashed curve). (b) and (c): Structures of the parasitic wave in cross sections of symmetric and asymmetric cavities.

We compare cavities with one groove and with two grooves spaced by the rotation angle of 150º (Fig. 4). If the groove is not exactly resonant for the operating mode, then it has different effects on two orthogonal $TE_{3,7}$ modes of stationary polarization. A single groove slightly disturbs the mode with the maximum of the field close to the groove, but do not disturb the second mode with the zero field at the groove. Due to this fact, simulations predict a fast increase in difference of frequencies of the two eigenmodes, Δf, with the change in the groove depth, δR, as the frequency of one of these modes is independent on δR (Fig. 4). This leads to stopping rotation of the wave when Δf exceeds f/Q. To avoid this effect, we place the second groove in one of the maxima of the operating wave field (Fig. 4). In this case, for any pair of orthogonal $TE_{3,7}$ modes of stationary polarization, the both these modes experience almost the same effects from the pair of grooves. Thereby, Δf stays small in a wide range of δR.

If the Q-factor of the operating 1 THz wave amounts few hundred, then the band f/Q is ~0.5 GHz. In the two-groove system (Fig. 4), the frequency difference Δf stays within this band, while the frequency of the rotating eigenmode varies within a band of ~ 3 GHz. Note again that this change in the frequency of the mode does not affect on its structure and, therefore, on the electron-wave interaction.

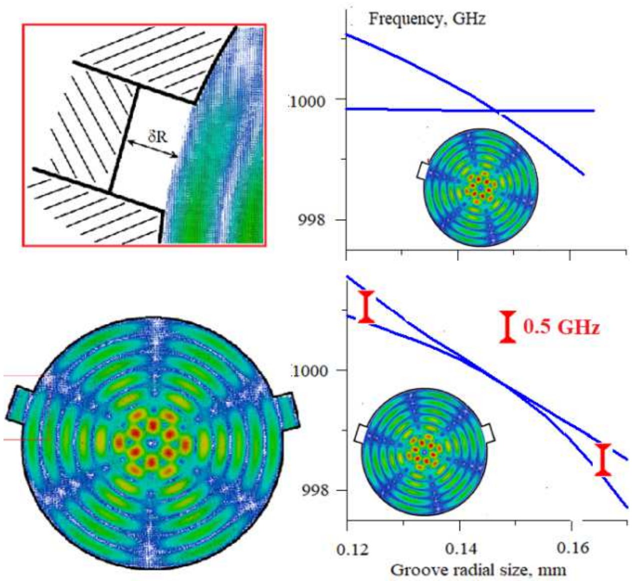

Figure 4. Schematic representation of a cross-section of a asymutaly asymmetric gyrotron cavity with depth-varying (variable δR) grooves Eigenfrequencies of two orthogonal stationary polarized waves TE3,7 in the cavities with one and two inhomogeneities.

In this example, the shape of the asymmetrical cavity is chosen from the point of view of the suppression of the parasitic oscillations and to achieve a quite high (1 THz) frequency in a third-cyclotron-harmonic gyrotron. Naturally, the use of this approach in less "extreme conditions" provides wider bands of frequency tuning. In this work, we describe our analysis of the possibilities for the use of this approach in various THz gyrotrons, as well as results of optimnizations of asymmentical cavities preformed on the basis of CST simulations.

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7 References

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