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Development of Terahertz-Range Planar Gyrotrons with Transverse Energy Extraction Operating at Cyclotron Harmonics

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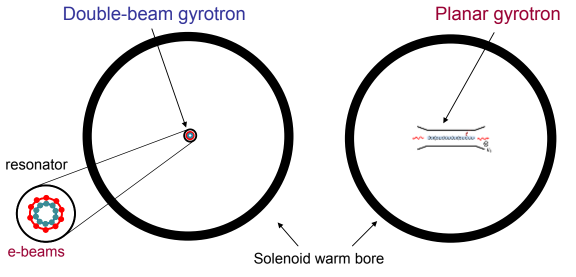
In the last few years, a considerable progress has been achieved in the development of terahertz-range gyrotrons [1-4]. At the frequency of 1 THz, the radiation power amounts several kilowatts in conventional gyrotrons with tubular helical beams formed by magnetron injection guns [1-3] and up to hundreds watts in large-orbit gyrotrons (LOG) with axis-encircling electron beams [4]. All these experiments were performed in the pulse regime. Recently, terahertz-range radiation at the second cyclotron harmonic was achieved. In the latter experiment, a superconductive magnet was used. The typical feature of such magnets is fairly large diameter of the warm bore of 5-10 cm. At the same time, the transverse cross-sections of conventional terahertz gyrotrons with cylindrical resonator are quite limited by several millimeters (Fig.1a). It is caused by problems with mode selection that restricted admissible waveguide radius and correspondingly the driving current. In order to provide starting conditions, one should increase interaction length above an optimal value that together with rather small cross-section results in substantial Ohmic losses. According to simulations for experimental conditions corresponding to [5], the Ohmic losses amount 80% of radiation power. Obviously, the improvement of mode selection is the key issue in the further development of short-wavelength gyrotrons.



(a) (b)

Fig. 1. Transverse cross-section of (a) a double-beam and (b) a planar gyrotrons in the scale of the warm bore of the JMTD15T52 cryomagnet.

For drastic increase in the output power of short-wavelength gyrotrons, we suggest to use the planar scheme with a sheet electron beam and transverse (with respect to the electrons translation velocity) electromagnetic energy extraction (Fig.1b). The main advantage of this scheme comparing to the conventional cylindrical geometry is the possibility of effective mode selection over the open transverse coordinate in combination with radiation out-coupling, which leads to substantial reduction of Ohmic losses [6]. It is important to note that in the existing cryomagnets, the warm bore is sufficient for a drastic increase of cross-sections of terahertz-range gyrotrons and provides enough space for installation of additional reflectors required for arrangement of transmission of generated radiation in the direction of collector.

An additional advantage of the planar scheme is the peculiarity associated with excitation of odd ($s=1,3...$) and even ($s=2,4...$) cyclotron harmonics. Under assumption that the sheet electron beam is injected in the middle of the cavity between the plates, the interaction at odd cyclotron harmonics occurs only for resonator modes with odd transverse indexes $n=1,3...$, while interaction at even harmonics occurs only for modes with even transverse indexes $n=2,4...$. Moreover, for example, for operation at the second harmonic it is beneficial to use an even resonator mode with indexes n equal to doubled even number. In this case interaction at second harmonic will be not accompanied by simultaneous excitation of a lower order mode at the first cyclotron harmonic due to the coupling factor for the 1st harmonic with an even mode is equal to zero. From the other hand, for excitation at the odd cyclotron harmonic the number of the resonator mode should not be dividable by s. For example, for $s=3$, the resonator mode number may be $n=5,7,11...$. In this case the parasitic mode at the 2nd cyclotron harmonic is not excited.

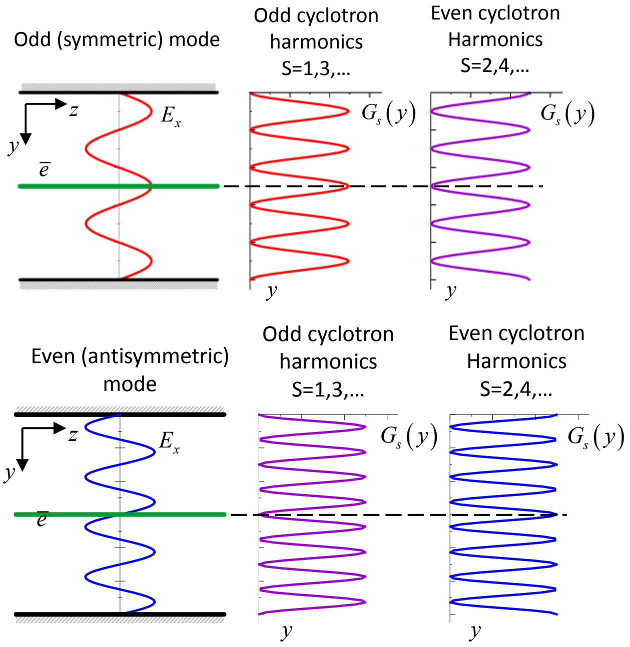


Fig. 2. The coupling factors $G(y)$ in a planar gyrotron.

Further results of simulations are presented for a 750 GHz second harmonic planar gyrotron with following parameters: accelerating voltage of 30 kV, electron current of 2 A, pitch-factor of 1.2, distance between plates of 4 mm, plates width and length were 8 and 17 mm, correspondingly. Simulations were carried out in the frame of averaged multiple modes averaged approaches:

$$s\frac{\partial a_n}{\partial \tau}+i\frac{\partial^2 a_n}{\partial X^2}+i\frac{\partial^2 a_n}{\partial Z^2}+\left(i\Delta_n+\sigma\right)a_n=\frac{I_n}{2\pi}\int\limits_0^{2\pi}p^s d\vartheta_0,$$

$$\frac{\partial p}{\partial \tau}+\frac{g^2}{4}\frac{\partial p}{\partial Z}+ip\left(\left|p\right|^2-1\right)=-\sum_n a_n\left(p^*\right)^{s-1}.$$

Here a_n is the amplitude of the $TE_{n,1}$ mode, p is the transverse electron momentum, Δ_n is the cyclotron resonance detuning, I_n is the parameter proportional to electron current and the coupling factor $G_n\left(y\right)$, σ is the parameter of Ohmic losses proportional to the skin depth.

In suggested scheme of gyrotron the diffractional extraction of radiation is realized in transverse *x* direction. Correspondingly at the edges of interaction space the nonreflecting boundary conditions may be applied. In the direction of translational motion of electrons the waveguide is closed by cut-off necks we can apply zero boundary condition along *z* coordinate.

In simulations competitions of operating $TE_{20,1}$ at the 2nd cyclotron harmonic and parasitic $TE_{9,1}$ modes at the 1st cyclotron harmonic was taken into account (Fig.3). The mode $TE_{20,1}$ doesn't excite due to corresponding factor $G_{10}\left(y\right)=0$.

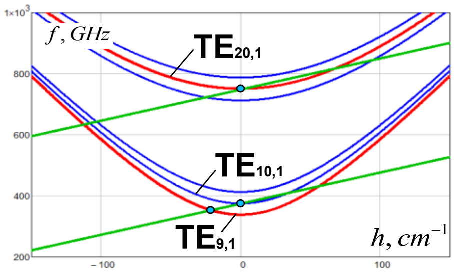
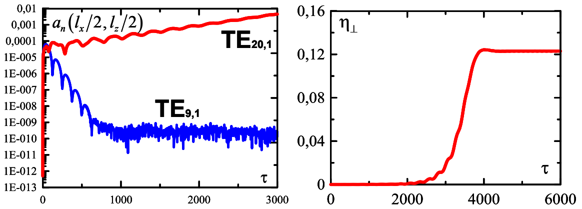


Fig. 3. Dispersion diagram of competing modes.

Results of simulations are presented in Fig.4. Figure 4a demonstrates the competition scenario. One can see that the excitation of the parasitic mode $TE_{9,1}$ is suppressed. As a result the single mode generation with excitation of the $TE_{20,1}$ mode is realized. According to simulations the transverse efficiency is of $\eta_\perp$ ~12% (Fig. 4b) and the total efficiency is η~7%. Taking into account that for chosen parameters about 30% of total radiation power is dissipated in Ohmic losses the output power is estimated of about 3 kW. It should be noted that in comparison with conventional gyrotrons, the suggested planar scheme demonstrates the high selectivity alongside with significantly lowwer Ohmic losses.



(a) (b)

Fig. 4. Temporal dependencies of amplitudes of competing modes (a) and the transverse electron efficiency (b).

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