Frequency Tuning and Spectrum Control in Sub-THz Gyrotrons

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Abstract: *We present the results of recent IAP RAS investigations, which were aimed at controlling the radiation frequency and spectrum of sub-THz medium power gyrotrons. Different methods of extending the smooth frequency tuning band and providing high frequency stability in CW regimes are discussed. The development of gyrotrons with stated parameters are of interest for many modern applications, including DNP/NMR and RAD spectroscopy, direct measurements of positronium hyperfine structure, diagnostic of various media, etc.*

Keywords: gyrotrons, THz-range radiation, frequency and spectrum control

Introduction

Traditional goal in the development of gyrotrons is associated with the power, efficiency and frequency increase. However, recently, other requirements became more acute in aspects of oscillations frequency and spectrum control. For example, for many modern applications related to spectroscopy, a CW oscillation regime with narrow radiation spectrum and wideband frequency tuning is in high demand at relatively lower (0.01-0.1 kW) power of THz radiation (see, for example, [1,2]). For a number of cases, this can be achieved by sacrificing the generation efficiency. Nevertheless, even with an efficiency of a few percent (much lower than a typical value of about 30%), the output power of gyrotrons will be several orders of magnitude higher than the power of classical BWOs and solid-state oscillators. Thus, control of the radiation frequency and spectrum of THz gyrotrons opens up new possibilities for scientific research.

Frequency Tunability in Medium-Power Sub-THz Gyrotrons

By now, gyrotrons have already demonstrated their prominence for spectroscopic applications, including signal enhancement of DNP/NMR spectrometers [3], application to radio-acoustic detection (RAD) to record the shape of spectral lines of large molecules [4], and for direct measurement of positronium hyperfine structures [5]. Nevertheless, for many spectroscopic applications, alongside with high radiation power, the large frequency tuning at the level of several percent is highly demanded. However, the standard value of the gyrotron tuning band is about a fraction of percent, which is associated with operation at the first near-cutoff axial mode with a sufficiently high Q-factor. Typically, for extension of the frequency tuning the excitation of high-order axial modes is used [6]. An increase in the number of excited modes can be achieved for a large normalized current parameter, which for given energy of the electrons, beam current and pitch-factor is provided by excitation of a low-order transverse mode. This possibility was experimentally studied for a fundamental harmonic 250-GHz gyrotron [7] operating at two modes, namely $TE_{5,2}$ and $TE_{0,2}$ (Fig. 1). For the $TE_{0,2}$ mode, the measured frequency tuning bandwidth reached 1.45 GHz and was limited by competition with the $TE_{2,2}$ mode at low magnetic fields and the $TE_{5,2}$ mode at high magnetic fields. The output power was measured by a calorimeter and ranges from 1 to 25 W. A wider band of frequency tuning was obtained for excitation of the $TE_{5,2}$ mode, since this regime is not restricted by mode competition. Generation takes place in a magnetic field range of 9.1 T to 9.38 T with a frequency tuning of 2.5 GHz of and an output power up to 15 W. Radiation at a low power level of 1 W or less was observed up to a magnetic field of 9.4 T. Based on these data, the full bandwidth of frequency tuning is extended up to 7.5 GHz. The relatively low obtained power at the first axial mode can be explained by deviation of the cavity geometry from the cylindrical one due to manufacturing inaccuracies.

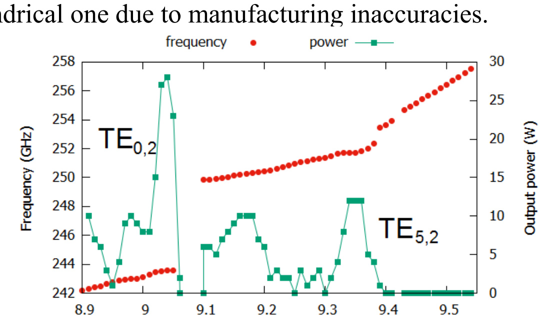

Fig. 1. Measured frequency tuning in the 250-GHz gyrotron operating with excitation of low-order $TE_{5,2}$ and $TE_{0,2}$ modes.

The disadvantage of frequency tuning by excitation of low-Q axial modes is associated with the widening of the radiation spectral line due to fluctuations of gyroton parameters. In the experiments, for a non-stabilized cathode power supply and a grounded anode, the measured spectral line width at the high magnetic field edge of the frequency-tuning band was about of 100 MHz at a level of -20 dB (Fig. 2a). It is 100 times greater than the spectral line width

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measured for a 263-GHz gyrotron operating at the first axial mode. In order to reduce the instability of the cathode voltage, a low-pass LC filter (L = 160 mH and C = 0.22 μF) was employed. Besides it, an anode low-voltage (about 1 kV) power supply with additional stabilization was used. Reducing voltages instabilities improved drastically the gyrotron spectrum at high-order axial modes. Figure 2b shows that the width of the central line decreased to 2 MHz. Along with the central line, there were some satellites in the spectrum, which are probably caused by low-frequency oscillations of the space charge between the gyrotron cathode and the cavity. These oscillations can be avoided in a gyrotron designed for operation at a lower pitch-factor.

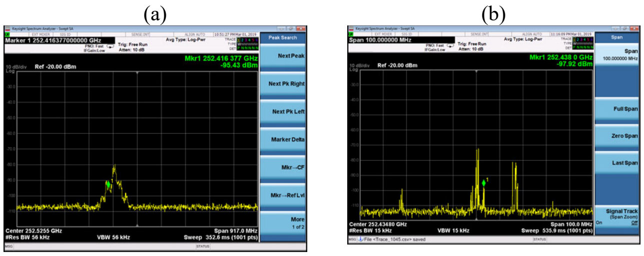

Fig. 2. Measurements of the spectral characteristics of the 250-GHz gyrotron without stabilization (a) and with stabilization of the cathode voltage using a low-pass LC filter (b). The guiding magnetic field of 9.38 T corresponds to excitation of the 3d axial mode.

One more possibility of wide frequency tuning in gyrotrons is associated with using cavities that is several times shorter than the value which is optimal for achieving the maximum efficiency [8]. In this case, the sensitivity of operation at far-from-cutoff high-order axial modes to the velocity spread reduces Based on this idea, the 163 GHz gyrotron with frequency tuning band of about 3-5% is currently being developed at IAP RAS. This tube is aimed to be used for RAD spectroscopy of quadrupole transitions of CO_2 at the frequency of 163 GHz.

Active and Pasive Methods of Frequency Stabilization in Sub-THz Gyrotrons

Active methods of frequency stabilization in gyrotrons utilize automated control of the electron beam parameters by variation of the guiding magnetic field, accelerating (cathode) voltage, and modulating (anode) voltage. Typically, it is provided by implementation of the so-called phase-locked loop (PLL), which is widely used in many types of oscillators. At present time, the maximum frequency stability was ensured in 263-GHz gyrotron on the basis of PLL scheme with modulation of the anode voltage [9]. This scheme combines a low current with a low capacitance, increasing the control system bandwidth.

The use of modulation of the anode voltage in the PLL system seems not obvious for gyrotrons, since without affecting the electron energy, it leads to a change in the pitch factor only. Nevertheless, simulations [10] show that variation of anode voltage can significantly change the radiation frequency in the zone of relatively low interaction efficiency which realizes at high magnetic fields (about 9.7 T in Fig. 3). Simultaneously, the weak output power modulation takes place with the reasonable level of 100 W which is more than enough for most spectroscopic applications.

In experiments [9], after applying the phase-locked loop, the width of the frequency spectrum was decreased from 0.5 MHz for a free-running gyrotron down to 1 Hz for the stabilized gyrotron. This corresponds to the relative frequency change $\Delta f / f \approx 3 \cdot 10^{-12}$ with a measurement time of a few seconds, which is several orders better compared with the previous experiments.

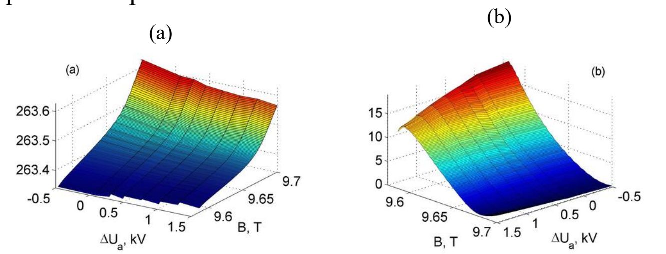

Fig. 3. Calculated dependencies of the 263-GHz gyrotron operating frequency (a) and efficiency (b) on the magnetic field and anode voltage.

The passive methods of frequency stabilization are based on gyrotron locking by an external signal or by the impact of reflected radiation on the gyrotron operation. In comparison with the PLL technique, these methods provide significantly low stabilization, but look simpler for the experimental implementation. In last model experiments [11] devoted to the influence of a signal reflected from a non-resonant load on the gyrotron operation regime of 28 GHz, the twofold decrease in the sensitivity of the gyrotron radiation frequency to variation of the magnitude of the magnetic field is observed (Fig.4). Simultaneously, the possibility of smooth frequency tuning in the band determined by the Q-factor of the gyrotron resonator and power modulation in a range up to 20% by displacement of the reflector was demonstrated.

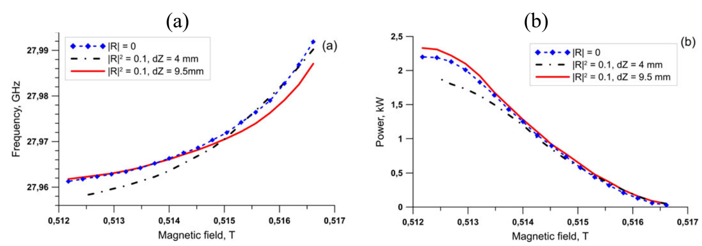

Fig. 4. Dependencies of the frequency (a) and power (b) of output radiation on the magnetic field for R=0 (without the reflector).

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