DEVELOPMENT AND APPLICATIONS OF HIGH POWER THz SOURCES WITH UNIQUE PARAMETERS: REVIEW OF IAP RESULTS

Mikhail Glyavin, Gregory Denisov

Institute of Applied Physics RAS, 46 Ulyanov str., Nizhny Novgorod, Russia

Abstract
This review aims to bring together information about the development and the most striking examples of high frequency gyrotrons applications. The paper describes the main features of terahertz gyrotrons. Some data about pulsed and CW tubes, working in the specified frequency range, are given. These gyrotrons demonstrate (in some specific combinations) extremely low voltage and beam current, narrow frequency spectrum, wide frequency tuning. Novel schemes of high frequency gyrotrons are analyzed.

Introduction

The last decade has contributed to the rapid progress in the development of THz sources [1-11], in particular of gyrotrons [2,4,6,9,10,11]. Although in comparison with the classical microwave tubes, gyrotrons are characterized by greater volume and weight due to the presence of bulky parts (such as superconducting magnets and massive collectors where the energy of the spent electron beam is dissipated), they are much more compact and can easily be embedded into a sophisticated laboratory equipment (e.g. spectrometers, technological systems, etc.) than other devices with a comparable value of Pf^2 such as free-electron lasers (FELs) and radiation sources based on electron accelerators. All these advantageous features have opened a road to multiple novel and prospective applications of gyrotrons as radiation sources in a great number of high-power THz technologies, advanced spectroscopic techniques, plasma science and materials processing, fusion research as well as in many other scientific and technological fields.

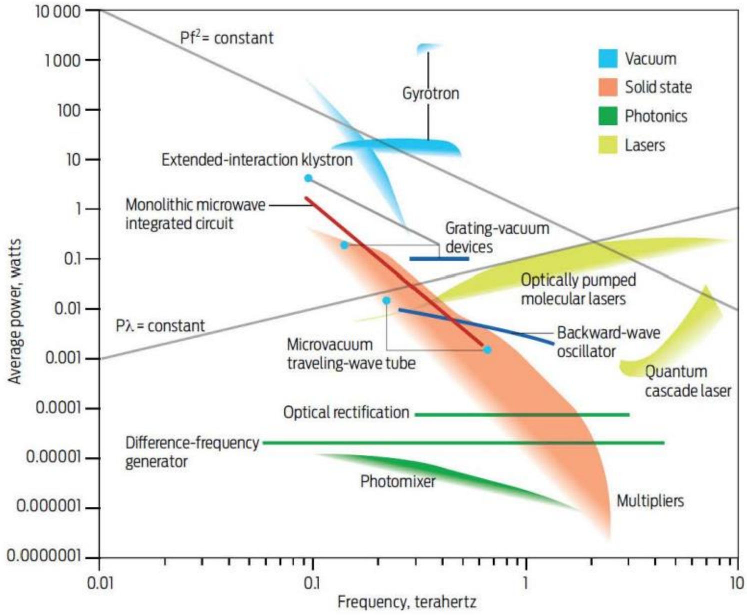

Fig.1 The THz sources "map" from Reference [5]

The gyrotron developed at IAP RAS jointly with GYCOM Ltd (Nizhny Novgorod) provides CW radiation with a power ranging from 1W up to 300 kW in the frequency range of 0.26 to 0.52 THz [12,13] and up to 1 MW at frequencies of 0.14 to 0.17 THz (Fig.2). It is important that power values up to 10W required for spectroscopy applications can be obtained at low voltage of about 1.5 kV or low beam current of tens mA.

Fig.2. 0.26THz/1kW/CW system with a liquid helium free JMTD10T100 cryomagnet (JA-STEC Ltd) at IAP RAS laboratory and 1 MW test facility in GYCOM experimental room.

It is well-known from the theory of gyrotron operation that the output power and frequency depend on a number of parameters including the magnetic field, the accelerating voltage, the beam current, and the electron pitch factor (velocity ratio); thus, the stability of the output parameters depends predominantly on the inevitable fluctuations caused by high-voltage power supply. In IAP RAS experiment, the anode voltage variation was used as a way of frequency control and stabilization, since lower anode currents reduce the requirements on the power supply while smaller capacitance of the modulating anode in relation to other electrodes increases the speed and performance of the control system. The experiment on frequency stabilization was carried out using a continuous-wave (CW) gyrotron [14] for spectroscopy and various media diagnostics operating at a frequency of 263 GHz with an output power of up to 1 kW utilizing an electron beam formed by a triode-type magnetron injection gun having an accelerating voltage of 15 kV and a current of 0.4 A, respectively. The gyrotron was designed for operation with a liquid helium-free cryomagnet (JASTEC JMTD-10T100) at $TE_{5,3}$ mode of a cylindrical cavity. The internal mode converter transforms the operating mode into a Gaussian beam. The phase-lock loop control of anode voltage was used and the width of the frequency spectrum was decreased to 1 Hz [15], which corresponds $\Delta f / f = 3*10^{-12}$ with a measurement time of a few seconds (Fig.3). The long-term stability was determined by reference clock ($\delta f / f \sim 10^{-9}$ for quartz clock and up to $\delta f / f \sim 10^{-12}$ for rubidium clock). Specified values of spectrum width and frequency stability have been achieved previously in backward-wave oscillators utilized in spectroscopy, although at power levels of tens of mW, while the stabilization system with anode voltage control in gyrotrons has no apparent limiting factors in gyrotron output power as it was demonstrated with an output power of 40 W.

It is interesting that the same scheme can be used for quick power modulation and data transmitting. Experiment was made based on 1kW/0.26THz tube and linear dependence between control (anode) voltage and output frequency was observed. As a result, high quality transmission of sound and pseudo random bit sequence (with a speed up to 1.5Mbit/s) has been obtained with leading role of IAP RAS members Drs. A.Tsvetkov and A.Fokin [16].

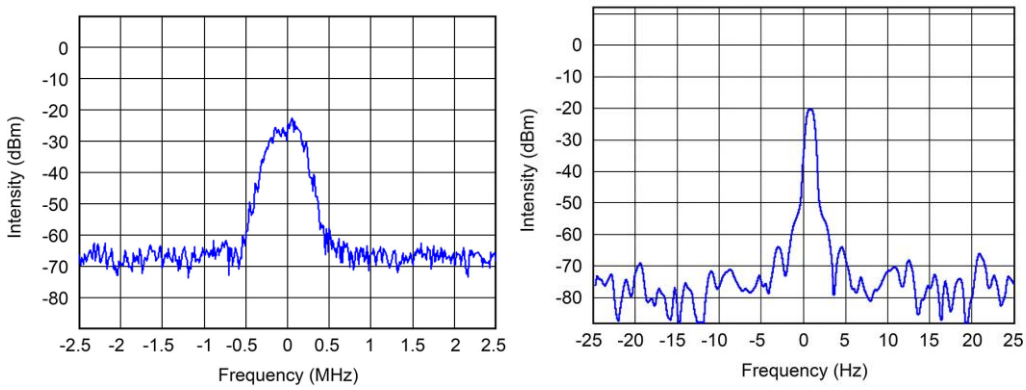

Fig.3. Experimental frequency spectrum of the free running gyrotron (left) and with phase-locked loop at an intermediate frequency with spans of 60 Hz (right) [16].

The prototype of CW 250GHz/200 kW gyrotron has been successfully developed. The power of up to 300 kW in 40 microsecond pulses with efficiency more than 30% has been obtained [17] in full accordance with theoretical estimation. The gas discharge experiments initiated by the microwaves under discussion demonstrate unique plasma parameters. The installation of a diamond window required for CW tests is in progress.

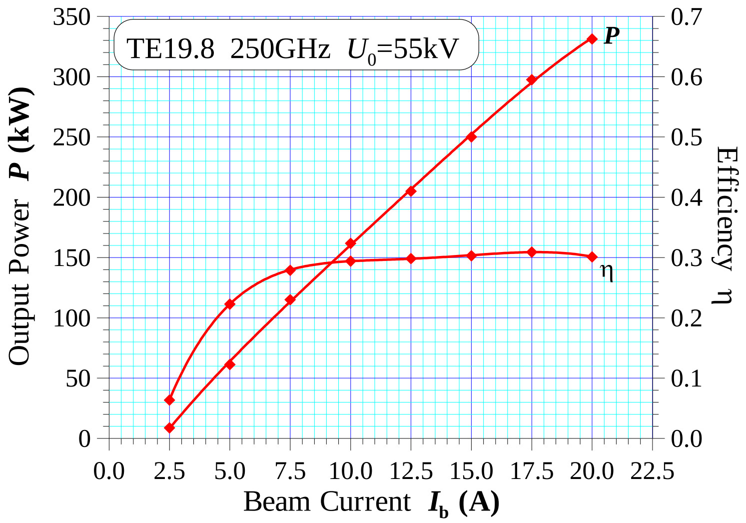

Fig.4. The output power and efficiency versus beam current observed at 0.25 THz gyrotron experiments [17].

The gyrotrons with pulsed magnetic fields operating at the fundamental harmonic produce up to 100 kW power level at 0.7 THz [18] and 1 kW at 1 THz frequency [19]. Potential increase of the operating frequency (especially, the excitation of higher harmonics due to the limited values of reasonable magnetic field) needs improved methods of mode selection, which can be divided into electron-optical methods and electrodynamical ones. The most successful realization of electron-optical methods is a gyrotron with axis-encircling electron beam (called 'large orbit gyrotron' (LOG)) developed by Prof. V.Bratman and Dr. Yu.Kalynov. The paper [20] presents the pulsed third harmonic 1THz tube with a power level several hundred Watts. CW version of LOG based on the cryomagnet is at the moment under manufacturing.

Second-harmonic CW gyrotron with improved mode selection based on double electron beam has been tested [21] jointly with FIR UF (Fukui, Japan). Wide step tuning of frequency by excitation of various modes was demonstrated in the range of 0.4-0.75 THz. Stable operation at the frequency of 0.76 THz at the second harmonic with a power level of about few Watts has been obtained, which is useful for modern NMR/DNP spectroscopy applications.

The projects of gyrotrons with "cold" (field emission) cathode [22] and low voltage (at the level 1.5-2 kV) are under development [23]. The complex cavities are under discussion for high harmonic excitation [24].

Feasibility of a high-power sub-THz gyrotron with smooth wideband frequency tuning suitable for direct measurement of the positronium hyperfine structure was demonstrated numerically using both averaged equations and PIC-code simulations. Analytical estimates show that the frequency tuning via excitation of axial modes can be achieved in a gyrotron with a short cavity driven by an electron beam with high current. Simulations [25] and preliminary experiments [26] demonstrated a possibility of wide-band (about 10%) fine frequency tuning. An output power of 0.5 to 1 kW can be obtained at a frequency of about 0.2 THz within a 10 GHz band, which are the parameters needed for testing of quantum electrodynamics predictions in positronium spectroscopy measurements.

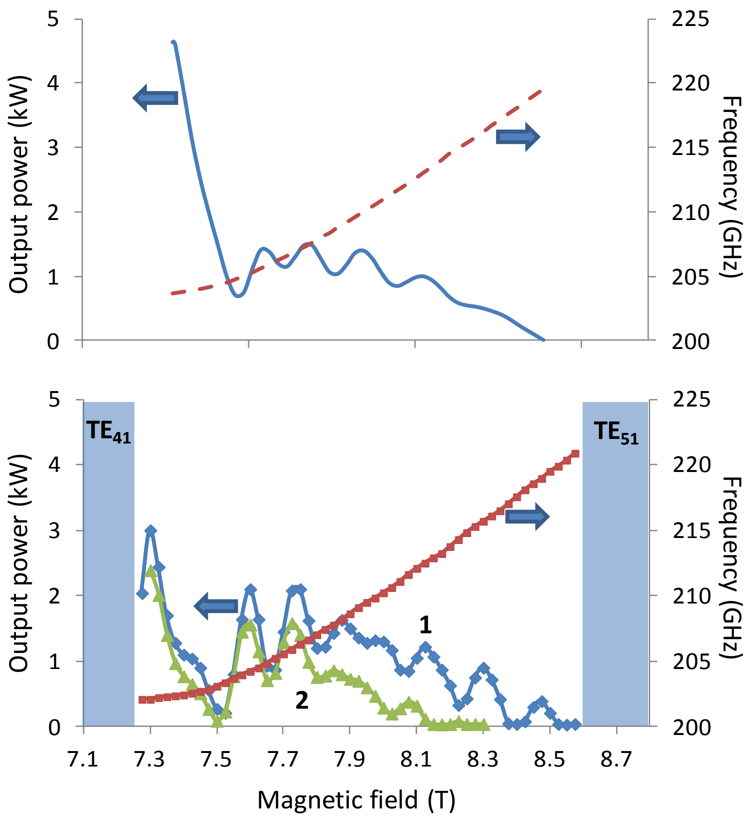

Fig.5. Gyrotron output power and radiation frequency vs. guiding magnetic field: the results of simulations based on self-consistent model for the cavity length reduced about three times in contrast with typical one (up) and the results of PIC simulations (down) for the same parameters and for two values of the relative transverse velocity spread, 20% (curve 1) and 50% (curve 2). The shaded area corresponds to the excitation of the parasitic modes [25].

Pulsed gyrotrons have been used successfully for initiation of localized gas discharges (Fig.6). Such plasma is promising for development of both a point source of multi-charged ions and a source of high-energy ultraviolet (extreme ultraviolet EUV or XUV) [27,28]. Gas discharge was also obtained successfully with 0.26 THz/CW IAP RAS gyrotron discussed above.

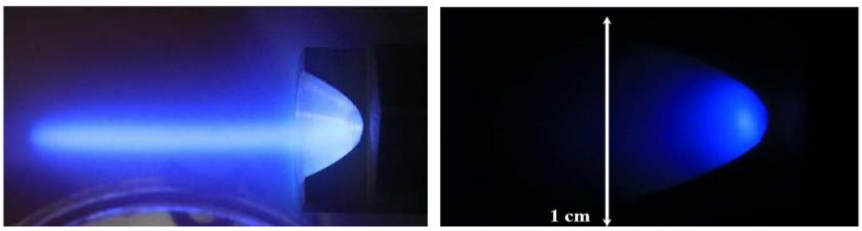

Fig.6. Gas discharge maintained at different initial gas pressure (left ~ 10^{-1} Torr, right ~ 10^{-2} Torr) by THz radiation. The signal from p-i-n diode corresponded to the power about 10 kW in a range 112-180 nm

The gyrotron looks as the most promising source for the high-resolution molecular spectroscopy in a gas mixture. A significant improvement of spectrum quality due to the output power increase in contrast with traditional BWO has allowed observing the theoretically predicted earlier transitions in SO_2 molecule [29]. Increasing the spectrometer sensitivity is obtained by increasing the radiation power which is suitable for transitions with a small dipole moment matrix element and nonlinear effects experiments as two photon absorption, detection of forbidden transition of nonpolar species, spin isomer conversion. Due to higher power, sensitivity of a radio-acoustic detector was increased in about three orders of magnitude. It is important to mention that in the course of the latest experimental campaign, we have used the radiated power not only on the fundamental harmonic, but also gyrotron radiation produced due to nonlinear effects at higher harmonic simultaneously with the fundamental. Though the generated power at the second and third harmonics is two orders and three orders of magnitude lower, respectively, than that at the first one, such a power level (1 to10 W) is significantly higher than in other sources. In this experiment, the SO_2 spectrum line was measured at the frequency range of 0.26 to 0.8 THz (Fig.7).

Continuous-wave gyrotrons (263, 395, 527 GHz) with a power of about 50 W give signal DNP/NMR enhancement up to 150 times [30].

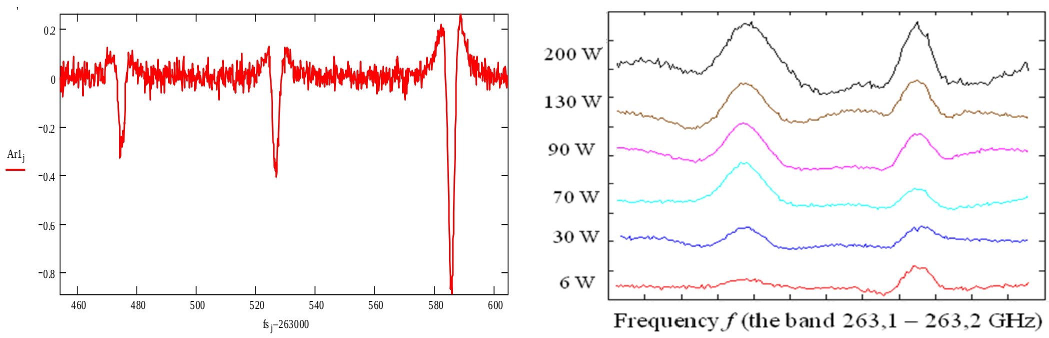

Fig.7. Examples of SO_2 spectrum for central frequency of about 0.5 THz and the spectrum lines measured with sensitivity of ~$8x10^{10}$ cm^{-1} [29].

Another interesting feature of powerful sub-THz radiation is high speed production of pure nanopowders by material evaporation and condensation. The use of a subterahertz gyrotron setup with an output frequency of 263 GHz and a nominal power of 1 kW as a radiation source to obtain nanoscale particles of metal oxides by the evaporation-condensation technique was demonstrated. Zinc oxide (ZnO) and tungsten trioxide (WO_3) were the test substances (Fig.8). The substance evaporation was provided by a focused beam of electromagnetic radiation with an estimated microwave-energy flux density of about 20 kW/cm^2 and was followed by deposition of the particles on the water-cooled surface. The sizes of the obtained particles ranged from 20 to 500 nm. An increase in the substance evaporation rate by more than three times in comparison with similar experiments using a technological gyrotron setup with a frequency of 24 GHz and a nominal power of 7 kW (the power density on the sample surface was about 13 kW/cm^2) as a radiation source was demonstrated. The increase in the radiation frequency leads to the improvement of the heating efficiency due to the increase of the absorption coefficient and provides greater power density due to better focusing of the radiation [31].

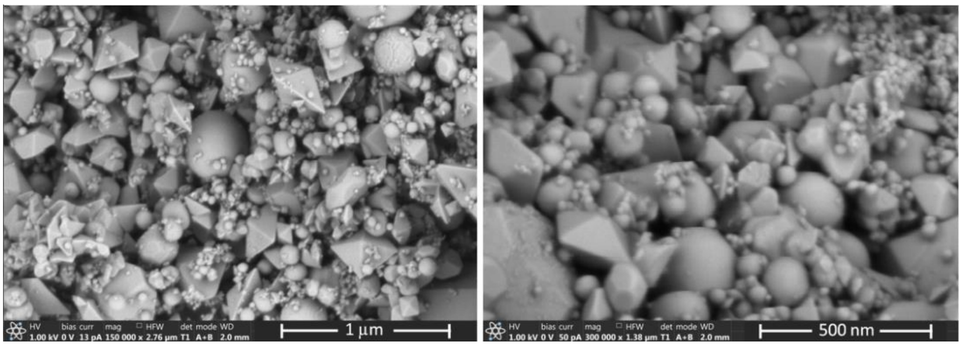

Fig.8. A microphotographs of the tungsten trioxide WO_3 nanopowder [30].

Despite the requirement for strong operating magnetic fields, mode competition, high ohmic losses, etc., the THz frequency range has been already achieved both by the pulsed and CW gyrodevices. The range of applications increases rapidly with the development of radiation sources.

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