Gyrotron Technology

Mariusz Hruszowiec, Wojciech Czarczyński, Edward F. Pliński, and Tadeusz Więckowski

Terahertz Technology Center, Wrocław University of Technology, Wrocław, Poland

Abstract—The article presents a microwave vacuum tube called gyrotron. Its applications, construction and principle of operation are briefly described. It is also discussed the issue of an appropriate electron beam generation and formation.

Keywords—beam gun, gyrotron, interaction of electrons with fast wave, microwaves.

1. Introduction

Microwave vacuum tubes are devices used for generation or amplification of the microwaves [1]–[13]. Microwaves cover a large part of the electromagnetic spectrum, and at the same time there are only a few kinds of devices operating in this frequency band, capable of operating with high power. This group includes amplifying devices, such as traveling-wave tubes (TWT), klystrons, gyro-TWTs, gyroklystrons and other. The generators are magnetrons, backward wave tubes (BWO), gyrotrons and other. Currently, the microwave vacuum devices are almost exclusively designed for amplification and generation of large and very large RF signals. While the range of centimetre waves and average power are dominated almost entirely by semiconductor devices, the high-output power ones, especially in the millimetre range, are still the domain of vacuum devices. Another advantage of vacuum tubes over semiconductor equipment is high efficiency, as yet unavailable for semiconductors.

History of the microwave tubes dates back more than a century, but it was during the Second World War when their role has become so important. Magnetrons and klystrons were used to build the radars. The traveling-wave tube, which was invented during the war, has been applied mainly in may military and communication systems.

The development of semiconductor technology has slowed down the development of microwave tubes. It was thought (70s of the 20th century), that vacuum tubes would be completely replaced by solid-state devices. Unexpectedly, this trend has changed in the beginning of the 90s, when it turned out that in satellite communication the TWT tubes are better than semiconductor devices [14]. In the same time the improvement of gyrotron, the device that has been invented a few years earlier, was impressive. This new tube has an important advantage, namely the area where interaction of electromagnetic wave and electron beam occurs is of simple geometry and does not require delay line with structure dimensions proportional to the wavelength as in devices such as klystron, magnetron or TWT. The delicate structure of the delaying lines and resonators limited their use at higher frequencies and high power levels. An additional advantage is the relatively high efficiency, which is being improved every year [18]–[21]. In addition, another factor that caused the big return of microwave vacuum tubes technology, was the power they can generate, especially in wavelength of millimetre waves. The power generated by gyrotron tubes may be several orders of magnitude greater than the power of a devices based on semiconductor structures.

2. A Brief History of Gyrotron

The operation of the device called a gyrotron is based on a phenomenon known as the ECR (Electron Cyclotron Resonance), instability of relativistic rotating electrons during the interaction, in a constant magnetic field, with an electric field of the electromagnetic wave [15]–[17], [23]. Theoretical work on this phenomenon was started by Twiss in Australia [24], Schneider in the USA and Gaponov in the USSR [25] in the late 50s. The first experiments were carried out and the results published by Gaponov and Pental in the 1959 [26]. Then the results of several experiments were mainly published by a group of scientists from the USA and the USSR [27]–[29]. The first working gyrotron was constructed by Hirshfield and Wachtel in 1964. The gyrotron with an annular magnetron electron gun with the adiabatic compression of the stream of rotating electrons and the cavity with smooth walls was invented in the Radio-Physical Institute, Gorki (now Nizhny Novgorod), in the USSR by Gaponov and Kiesel [27] in 1963. Figure 1 shows a scheme of the first gyrotron [16]. The output power of 6 W was obtained in the continuous work mode at the 10 GHz frequency. The use of a MIG (Magnetron Injection Gun) electron gun and a single cavity has delivered significant power output with a very good efficiency,

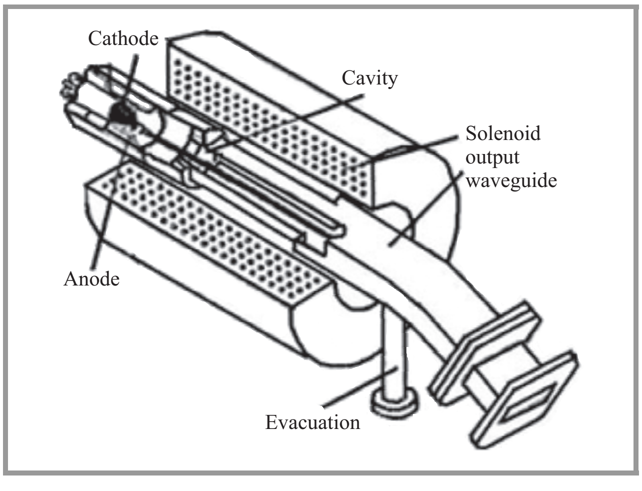

Fig. 1. Construction of the first gyrotron.

compared to the previous experiments. Later the new experiments were conducted with the gyrotrons working at higher harmonics and generating higher output power [16]. In the years 1970–1980 a significant progress was has been done, both in the theoretical and experimental field, including the theory of gyrotron and other devices based on extracting energy from the gyrating electrons, such as gyro-klystron, gyro-TWT, etc. There were also other experiments conducted in order to improve both the efficiency and the output RF power. They were focused mainly on the proper profiling of the cavity (area of interaction), elimination of the parasitic oscillation, increasing the work frequency and the development of tunable gyrotrons [30]–[34]. The use of helical output launcher developed by Vlasow in 1975 allowed the conversion of multimode wave into a Gaussian distribution mode [35]. In the 80s the work on gyrotrons has been started in many other countries such as Brazil, Korea, France, Japan, Australia and Germany. In the years 1990–2000 a significant development of terahertz and coaxial gyrotrons was done. During this period, the FZK Karlsruhe team, working for the ITER project has made the most significant progress [36]. Extensive investigation and production activities were carried out in USA, Japan and Russia. At present more countries like India and China, have started to work on their own gyrotrons. We expect that in the near future, Poland will also join this elite club. Initial research has already been done by the Wrocław Terahertz Team [37].

3. Applications

Gyrotron has found many applications in many different areas such as communication, military applications (from radar to missile guidance systems), science (elementary particle acceleration, thermonuclear plasma devices, diagnostics), industry (heating, processing of different materials, e.g. ceramics) and in medicine, i.e. innovative methods of cancer therapy, high power terahertz radiation [38]. Some of these applications will be briefly presented below.

3.1. Communication

Because of the considerable attenuation of electromagnetic radiation in the Earth's atmosphere along with the increase of the wave frequency, the present communication systems need to be improved in order to continue their tasks, including future demand for quick transfer of very large data quantities. Future microwave systems should also be able to generate high power required by the radar systems working in the millimetre wave regime, providing long range and high resolution. Microwave tubes, and in particular the gyrotrons that work at high frequencies, are among a few devices that can be used in these applications. In addition, these devices can provide microwave power for radars tracking space junk, as well as for georadars, which detect the underground structures, such as bunkers, mines, pipes, and other. Additionally, the latest terahertz gyrotrons can generate teraherz frequencies radiation, which in turn can be used for inter-satellite communication (due to the wide bandwidth) and for communication at short distances, which can be very useful in military applications.

3.2. Defence Applications

The gyrotron that works on the frequency of 95 GHz and with output power of 100 kW was used as a source of millimetre radiation for ADS (Active Denial System). The ADS System was developed by Raytheon for the U.S. Army Air Force. It is a not lethal, anti-personnel, weapon that uses the directed energy. Officially published data provide information about effective coverage within the limits up to 1 km. The available materials about the ADS reveal the frequency of work to be 95 GHz, probably chosen because of a natural window of low atmosphere attenuation in this frequency range. The depth of skin penetration of the wave of this frequency range is about 0.4 mm and after 2 seconds causes rise of the water temperature in upper layer skin up to 50–60°C, causing a hard to stand feeling of pain. Turning off the beam causes almost immediate relief of symptoms. The exposure of skin causes no permanent effects, but the beam of sufficient power and duration can cause eye damage and even second degree burns. Published data show that the effective power density is approximately 2 W/cm^2. The countermeasures are very simple, the thicker layer of clothing or metal foil [39]. There is no data on the effectiveness of that weapon in the rain, fog or snow. Local conditions, including climate, resulted in the withdrawal of ADS from Afghanistan in 2010 without its use. In the year 2010 the Los Angeles police (USA) was equipped with such weapon for tests [41].

The millimetre wave radars were developed, which allow to obtain high location resolution of tracked objects [42]. In addition, thanks to the gyro-sources, the effective range rises up to several hundred kilometres, which is a remarkable result especially together with high resolution imaging. Currently such radars are working in Russia and in USA. The Russian installation consists of a matrix of 120 antennas, works at 34 GHz frequency. It is fitted with two gyro-klystrons, 0.5 MW output power, bandwidth of 50 MHz, and the duration of the pulse of 100 μs each. The American installation is based on the gyro-klystron that works at 94 GHz (92 kW of output power) with about 420 MHz bandwidth [43].

3.3. Meteorology

A high power signal of a millimetre wave can be easily used in all kinds of research concerning the structure and behaviour of the Earth atmosphere e.g. monitoring of clouds, humidity measurement, detection and identification of turbulence structures and other [44]–[46]. Radar systems operating at the frequency of 35 GHz and 94 GHz can easily be used to detect turbulence. In addition, the teraherz radiation can be used to study the water content in the atmosphere [48].

3.4. Defense of the Planet

Another possible application of the source of high power teraherz radiation is monitoring of the outer space. It is becoming more and more polluted by various types of space garbage and waste (old satellites, rocket modules, components, etc.), which are becoming a serious problem for the active satellites and other space vehicles. Because space debris detection and accurate maps of their orbits become necessary in order to ensure an appropriate level of security. For the system, which has been proposed by Chang and other, it is estimated that for detection of an object of 1 cm size at a distance of 1000 kilometres, the 20 MW signal and antenna with a diameter of 20 metres are needed [49]. Gyrotrons that work in the regime of 35 GHz are currently the best sources of radiation needed for detection of space debris.

3.5. The Topography of the Planet, Maps

The radiation of millimetre wavelength could be used to prepare topological maps of the planets [50]. The radiation beam would be focused on the surface of the planet, while the scattered radiation, depending on the topography of the area, would be detected by the radar system. As a source of radiation a miniature gyrotron could be used.

3.6. Security

A possible use of the gyrotron is the remote detection of various undesirable substances. The radiation has got already a number of applications, with the ability to penetrate a non-conductive and non-polar materials such as clothing, paper, wood and other. Such properties of terahertz radiation makes it suitable for applications in the area of public security, e.g., already operating scanning systems in airports or envelope content inspection systems [51]–[52].

An experiment was conducted, in which the radioactive substance was remotely detected using a specially designed gyrotron (670 GHz, 300 kW). The method was based on focusing the beam of THz radiation (produced by the gyrotron) on a small area (point), in which the amplitude of the electromagnetic field could exceed the discharge threshold and caused the air breakdown. Such a system may be used for remote detection of radioactive materials e.g. in containers or vehicles. This makes a new application field of both (sub)terahertz radiation, and the gyrotron as a source of this radiation [53].

3.7. Scientific Applications

The demand for the high power and high frequency radiation sources has been present from the beginning of modern science, particularly in physics of elementary particles and in fundamental research. Recent years have shown that especially applications in plasma and nuclear fusion research require dynamic development of the gyrotron technology. In many various tokamaks around the world, are already working the first gyrotrons. The gyrotron plays a very important role in plasma research already for the last 30 years. The latest international programme focused on the creation of the reactor capable to carry controlled nuclear fusion is the ITER programme. This programme is the largest one in progress, where gyrotrons will be working with the 170 GHz frequency and generating output power of 1 MW. High output power, high efficiency and long pulse of generated radiation are key requirements for gyrotrons in ITER project.

Another area of application of the radiation generated by the gyrotrons are the different techniques of investigation of structure of materials. One of these techniques is electron spin resonance (ESR), as a tool for studying of material microstructures [54]. Currently, this technique is used in the X-ray band, however thanks to the strong sources of terahertz radiation it is possible to use it for investigations of materials with a very short relaxation time.

The large terahertz signal is required in the dynamic nuclear polarization used together with the nuclear magnetic resonance (NMR/DNP) [54]. The nuclear magnetic resonance (NMR) uses strong pulse of electromagnetic radiation, which is then tested in terms of emission and absorption. The disadvantage of this method is the very low level of the recorded output. To increase the efficiency of NMR a phenomenon of electron spin transfer into the nucleus is used (Dynamic Nuclear Polarization, DNP). NMR is a very powerful tool in the bio-molecular analysis of protein and peptides structures. NMR/DNP spectroscopy in low magnetic fields is used to study polymers. On the other hand, for biological molecules (proteins) a strong magnetic field is required. For NMR/DNP that uses strong magnetic fields, high frequency and long radiation pulses, the low power gyrotrons are used as teraherz radiation sources.

The mentioned improvements of the classic diagnostic methods may be also applied in the future medical diagnostics. Other medical applications (e.g. therapeutic applications) are being examined. Presently there is an ongoing development of new hybrid therapy against cancer [55]. THz radiation, generated by continuous-wave gyrotron was used. The frequency range was from 200 GHz to 305 GHz, with the maximum power of up to 20 W. The tests, which were performed on laboratory mice gave the positive results, the growth of cancer cells after exposure to the radiation was stopped [54], [55].

3.8. Industrial Applications

In metallurgy applications microwave radiation in the range from 300 MHz to 300 GHz is mainly used for heat treatment of materials. Microwave heating is used in the processing of rubber, ceramics sintering, technology of chemical processes, production of composites, food industry. In some applications the millimetre waves have better properties than the centimetre ones. They are used in the following types of heat treatments: strengthening of surface, drying, removal of organic binders and moisture from the ceramics surface, growing of ceramic nanostructures. The gyrotron, is able to provide output power ranging from hundreds of kilowatts to several megawatts in the regime of millimetre wavelength. Gyrotrons may be installed inside the final devices because of high stability of generated frequency and power level. The millimetre waves in material heating surpass the use of centimetre waves in some applications because attenuation of electromagnetic radiation in dielectric materials increases with frequency and the heating efficiency is better than for centimetre waves. Due to the shorter wavelength the depth of penetration is smaller and the incident radiation power is lost in the shorter depth, allowing the near surface treatment of the material.

4. The Construction and Method of Operation

The gyrotron in its basic configuration consists of the following parts: the source of the electron beam (electron gun), magnets or solenoids producing a static magnetic field, cavity, output circuit and collector. As the output system a special launcher with set of mirrors can be used, in order to guide the electromagnetic wave perpendicular to the axis of the gyrotron or along with main axis of the tube using a special electron collector ended with a in-axis vacuum-tight window, which transmits the output signal out of the tube. A schematic diagram of the gyrotron is presented in Fig. 2. The annular electron beam is generated by an annular magnetron electron gun. The external magnetic field, usually generated by a liquid nitrogen cooled solenoid or superconducting one. The magnetic field increases gradually from low value at the emitting cathode surface (should be almost parallel to the surface to obtain a quasi laminar electron beam) to the value required for the desired cyclotron frequency. The increase of magnetic field causes compression of the average diameter of the annular beam. The maximum magnetic field occurs in the region of the resonance cavity, and its value (together with the accelerating voltage of electrons) specifies the electron cyclotron frequency and thus the tube frequency of operation. The relationship between the wavelength, magnetic field and voltage is given by the formula:

$$B\ [\mathrm{T}] = 10.7\gamma/s\lambda\ [\mathrm{mm}]\,, \tag{1}$$

where $\gamma = 1 + \mathrm{V}$ [kV]/511 is the relativistic Lorentz factor, s is harmonic number of operation, λ is the wavelength in millimetres [56]. It follows that for a wavelength below 1 mm at the fundamental harmonic and with accelerating voltage of 50 kV, the magnetic field must exceed 10 T. To obtain such high fields the use of a superconducting solenoid is required. To reduce the requirements for magnetic field, higher harmonics are often used, at some expense of efficiency. However, achievable conversion efficiency for the second harmonic can be even 35% [57].

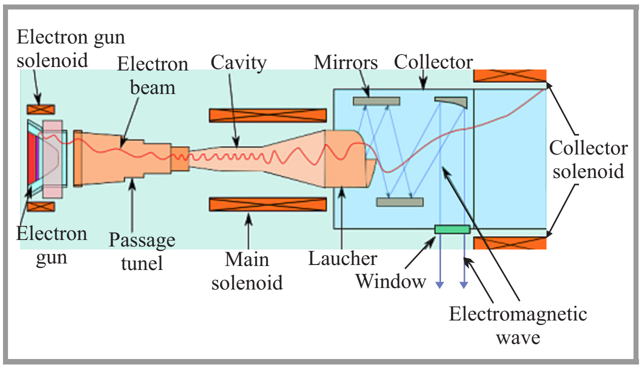

Fig. 2. Gyrotron sample construction scheme.

Rotating electrons move to the cavity into the electron-wave interaction area. In this area the electrons are retarded by the electric field of the electromagnetic wave, thus a portion of their energy is transferred to the electromagnetic (EM) wave. The magnetic field in the interaction area is chosen in such a way that the frequency of an electron cyclotron resonance, or one of its harmonics, close to the desired EM wave frequency. In axial gyrotron the electron beam is captured by the walls of a hollow coaxial collector, due to reduction of the axial magnetic induction (almost zero), while the electromagnetic wave is transmitted out of the tube through the axial vacuum-tight window at the end of waveguide collector section. In the radial type of the gyrotron output, the vacuum-tight window is perpendicular to the main gyrotron axis (Fig. 2) [58].

The main working component is the cavity, where the interaction of the beam of rotating electrons, and electromagnetic wave takes place. Usually it is an open round resonator with smooth walls, whose main section is ended on both sides by short sections with tapered diameters, causing partial reflections of electromagnetic wave [15]–[17]. The first section should present the reflection coefficient as high as possible, preventing passage of the EM wave back to the electron gun, whereas the output section should the reflection coefficient rather low. Beam-wave interaction occurs mainly in the central part of the resonance cavity, while the last section is used for coupling the cavity with a launcher or the output waveguides. Coaxial cavities are also used, because the distribution of electric field, associated with electron beam space charge, is more favourable. This allows for higher efficiency of energy transformation. However, the coaxial gyrotrons have more complicated structure of the electron gun.

The electron trajectories are helical with the axes of rotation along the lines of the static magnetic field. In order to extract energy from the rotating electrons and to transfer it to EM wave, the electrons should be focused in phase on their cyclotron orbits. Such focusing makes possible the net extraction of electron energy to the wave. To take benefit from such mechanism, it is required to satisfy the resonance condition between the periodic movements of electrons and EM wave in the interaction section, according to the following formula [15]–[17]:

$$\omega - k_z v_z = s\omega_c\,, \tag{2}$$

where ω is the EM wave frequency, k_z is the axial characteristic wave number, is the electron drift velocity, v_z is harmonic number, and ω_c equation stands for the cyclotron electron frequency. Because of very high energy of the electron beam, the frequency shift occurs $(k_z v_z)$, which is caused by the relativistic Doppler effect. In the gyrotron the electron drift velocity (v_z) is always lower than the transverse electron velocity, what causes that Doppler effect may be neglected. In such case the cyclotron resonance condition can be written down in the following way:

$$\omega \approx s\omega_c \,. \tag{3}$$

4.1. The Electron-optical System

The gyrotron electron-optical system consists of a launcher, tube tunnel and electron collector. Part of the tunnel tube is a cylindrical or coaxial resonator, where the electron beam is rotating around the main axis of the cavity.

A critical element of the gyrotron is the source of electrons, which should generate a laminar beam. The electron gun is of a magnetron injection type [59]. Two kinds of electron gun are used: a diode in the cathode-anode configuration and a triode in the cathode – modulating anode – anode configuration. Diode MIG launcher has a single anode and its construction is much simpler than the triode type, which has two anodes and requires two separated supplies and additional high voltage gun insulator. However, the use of modulation anode provides better control of the electron beam.

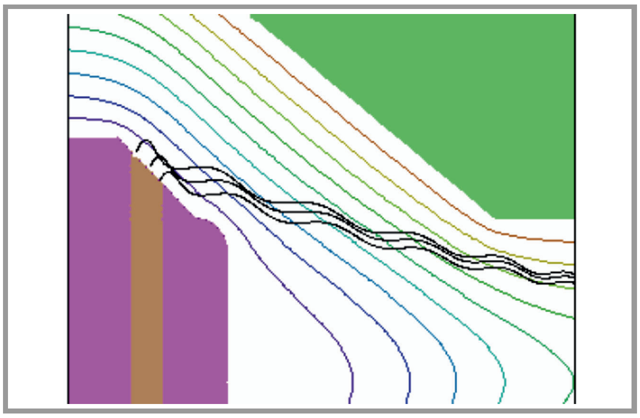

Fig. 3. Quasi-laminar electron trajectories in the magnetron injection gun. The cathode emission is confined by the space charge. $U_a = 55$ kV, $B_z = 4.3$ T. The electron trajectories are started from edges and centre of the emission layer.

Electrons emitted from the cathode are accelerated towards the anode, forming a beam of relevant parameters (Fig. 3) [37]. Magnetic field lines should be parallel to the electrons emitting surface. The increase of magnetic induction towards the cavity causes adiabatic compression of diameter of the electron beam in the tunnel between the electron gun and the cavity. The transmission tunnel is often equipped with damping elements to prevent a microwave signal from going back into the gun area. The external diameter of the gyrotron is determined by the maximum internal diameter of the magnetic system.

The ratio of the accelerating voltage to the magnetic field determines the cyclotron frequency and the ratio of radial velocity of the electron to its axial velocity, which is along the axis, around which the spiral movement occurs. The radial velocity of the electron determines the amount of possible extracted energy. However, the pursuit of excessive increase of it can lead to magnetic mirror formation and reflections of the electrons back into the source. The ratio of radial velocity to the axial velocity α is usually about 1.2. The trajectories of the electrons are helical along the magnetic field lines. The change of the magnetic field from B_0, at the cathode, to the $B_{\max}$ at cavity, is determined by $F_m = B_0/B_{\max}$, called magnetic field compression. This factor determines the change in diameter of a annular electron ring beam.

The function that describes the change of the magnetic field, $B_z = f(z)$ must comply with certain conditions (such as field lines must be approximately parallel to the emission surface), that is why the gyrotron electron gun is often equipped with a separate adjustment solenoids [60].

Because of the very important role of the electron gun, the effort was made to perform numerical simulations of such devices. Simulations were performed using the Amaze (Field Precision) set of codes for calculations of electric and magnetic static fields and electron trajectories. The simulated gun was a typical diode with a cathode and a single anode (Fig. 3), working in the space charge limited emission regime. The obtained results were quite promising. Simulated beam of electrons showed good laminarity. It is interesting because the electron guns that work in the temperature limited current mode are able to emit quasi-laminar beam easily, on the other hand emission from the

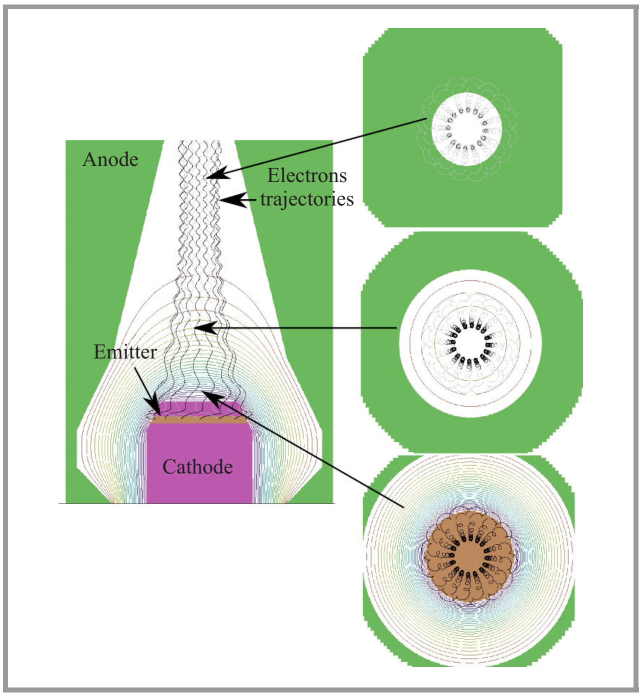

Fig. 4. The electron trajectories in magnetron diode gun. The 16 trajectories of 160 used in simulation are shown.

cathode that works in spatial charge mode is more uniform [61]. Figure 4 presents the electron trajectories in transverse planes in the tunnel as seen from the resonator side [37]. Note: Fig. 4 presents another configuration of the electrodes and fields than Fig. 3.

4.2. The Resonator

Construction of the resonator is very simple. It is a cylinder or section of a coaxial line. The resonator is ended on the side of the electron gun by a short tapered section, which has different impedance, causing reflection of electromagnetic wave. Because this kind of resonator ending does not cause complete reflection, the passage tunnel is usually fitted with means for suppressing of the EM signal in the direction of the electron gun. Attenuation is achieved by suitable design of the tunnel walls, by lining them with damping material or by both methods. The other end of the resonator is a funnel shaped transition section passing into the multimode waveguide. The reflection coefficient is sufficiently low to allow the flow of the generated signal. It should be noted that the reflection towards the cavity is not necessary for signal generation. From any point, where the exchange of energy between the electron and the electromagnetic wave occurs, the wave propagates in both directions, as in classic Backward Wave Oscillator (BWO), whose counterpart is the described type of gyrotron.

4.3. The Output System and the Collector

Two types of signal output systems are commonly used in gyrotrons. In the first type the resonator output is transformed into a circular waveguide, whose walls act simultaneously as collector of electrons. The magnetic field in this section should be reduced to zero. The electrons under the influence of the spatial charge and not focused by the magnetic field, are guided towards cooled walls of the waveguide. There is often an additional solenoid producing crossed magnetic field, which is directing the rest of electrons to the walls of the collector section of output waveguide. It is necessary for the protection of vacuum-tight window, closing the vacuum part of device. Even a minute electron bombardment of the dielectric window might initiate its destruction by the multipactor effect.

The second solution involves the guidance of the signal perpendicularly to the main axis of the gyrotron. The signal is directed from the waveguide following the resonator by means of the Vlasov launcher into the system of the transformation mirrors, that changes the multimode signal into a coherent one [62], [63]. It is directed by the vacuum-tight window to the receiver. The electrons in this solution are moving along the axis of the gyrotron into the collector, which is not the part of the waveguide, so it can be isolated and can be at lower potential than accelerating voltage. Such solution allows for partial energy recuperation and thus for improvement of the overall efficiency. The price for that is a complexity of the structure (additional high voltage insulator and additional high voltage collector supply). Such type of collector is commonly used in high power linear microwave tubes and satellite TWTs, whose the overall efficiency is an important parameter.

The microwave vacuum-tight windows, especially for the high power and for continuous wave may be quite a technological problem. The best (and the most expensive) are the diamond ones, primarily due to the high thermal conductivity of diamond. Usually the windows are cooled.

4.4. Magnet

As it is clear from Eq. (1), a gyrotron requires very strong magnetic fields, inversely proportional to the wavelength of the signal. These fields can, in extreme cases, reach up to 20 T. The medium size gyrotron that generates wave longer than 1 mm still requires several Tesla magnetic field. One of the solutions is to work with harmonics higher than the first one. High power gyrotrons, stationary and designed for work without interruptions, generally are fitted with magnets placed in cryostats and cooled with liquid nitrogen.

For stronger fields superconducting solenoids are used, placed in liquid helium. This solution excludes its application in mobile devices, because the usual practice is keeping the magnet in the cooled state. Preparation from ambient temperature to the work one requires many hours of cooling down and large amounts of liquid helium. Maintenance in a state of continuous readiness is also very expensive. The search for better solutions, especially for mobile applications, led to the development of solutions based on permanent magnets and classic solenoids. For few millimetre wavelengths liquid-cooled solenoids are successfully used. Pulsed solenoids are also tested. Presently the permanent magnets can generate magnetic fields just above 1 T in the volume of resonant cavity [64]. There are also reports on conventional solenoids that were able to produce 1.8 T and 2.1 T [57], [65]. The first of them was the solenoid made with copper foil, placed between liquid-cooled copper plates. The second solution was the solenoid made of copper tube, cooled with liquid.

4.5. Technology

Gyrotron technology does not much differ from the metal-ceramic tube technology of high power TWT and it does not present serious problems. Such technology is fully available in Poland.

5. Summary

The gyrotron undoubtedly is one of the most promising devices. It is currently the object of very extensive research around the world. The article mentions some possible applications of such devices. The principle of operation and construction has been described briefly. Particularly, attention was focused on the electron beam generation, and more specifically on magnetron electron guns.

The required parameters of the electron beam, formed by the electron gun in gyrotron, were described. The results of simulations of the electron gun, intended for gyrotron application, first in Poland, have been presented.

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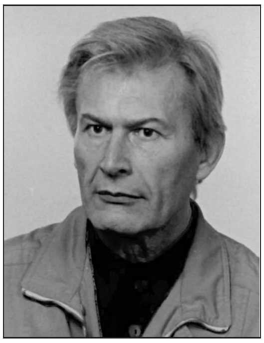
Mariusz Hruszowiec graduated Applied Computer Science at the Wrocław University of Technology in 2012. At present he is Ph.D. student at Faculty of Electronics at the Wrocław University of Technology. The main topics of his interest are gyrotron theory, electromagnetic field theory and numerical methods.

E-mail: mariusz.hruszowiec@pwr.edu.pl
Telecommunication and Teleinformatics Department
Wrocław University of Technology
Janiszewskiego st 9
50-370 Wrocław, Poland

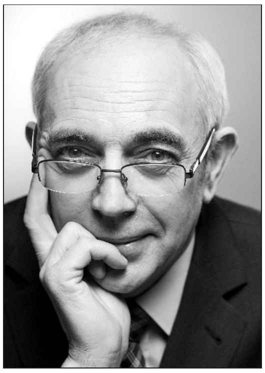


Wojciech Czarczyński received the M.Sc. Eng. in Electronics from the Wrocław University of Technology, Poland, in 1957. From 1956 to 1964 he was with the Industrial Institute of Electronics, Wrocław Branch (PIE). In the years 1964–1965 he was Research Fellow on ONZ Fellowship at the Southampton University involved in the design and research in the field of power microwave tubes. From 1965 to 1978 he was again with PIE as a head of microwave tube laboratory. In 1956 he received the Ph.D. degree in the electron beam research from the WUT. In 1978 he joined the Institute of Electron Technology, WUT, where he was involved in electron beam and plasma research. He was appointed the Institute Head for the 1987–1990 term. In 1995 he received D.Hab. degree from the Faculty of Electronics, WUT and was appointed University Professor. In 2001 he became full professor. He retired in 2003 and was a part-time research worker till 2008. Currently is the voluntary member of the Terahertz Center of the WUT, Wrocław, Poland.

E-mail: wojciech.czarczynski@pwr.edu.pl
Faculty of Microsystems Electronics and Photonics
Wrocław University of Technology
Janiszewskiego st 11/17
50-372 Wrocław, Poland

Edward F. Pliński received the Diploma degree in Physics, with specialization on Solid State Physics, from the University of Wrocław, in 1974 and the Ph.D. degree in Technical Sciences, with specialization on carbon dioxide lasers, from the Wrocław University of Technology in 1983. In 1985, he joined the Twente University, Enschede, the Netherlands, where he worked with a Professor W. J. Witteman's group on a waveguide carbon dioxide laser technology. In 2002, he received the D.Sc. degree in technology of RF excited carbon dioxide waveguide lasers. In 2006, he changed his subject of interest and he established the Wrocław Terahertz Team. From 2012 he is heading the Wrocław Terahertz Center at the Wrocław University of Technology. Currently, his subject of interest is terahertz technique and technology.

E-mail: edward.plinski@pwr.wroc.pl
Faculty of Electronics
Wrocław University of Technology
Wybrzeże Wyspiańskiego st 27
50-370 Wrocław, Poland



Tadeusz Więckowski specializes in the field of electromagnetic compatibility of device, systems and installations, in particular the intersystem compatibility of radio communication and telecommunication installations. He is the author of over 175 scientific publications, 6 patents and patent issues, and over 600 elaborations on economy. With the support of his colleagues he initiated, created and promoted the world class Electromagnetic Laboratory of Compatibility. One of his greatest successes is the creation of the Knowledge and Innovation Community for Information and Communication Technologies, and The Academic Incubator of Entrepreneurship at Wrocław University of Technology. For his scientific and teaching activity and cooperation with industry Professor Więckowski was twice awarded by the Prime Minister of Poland. He was honored with the Golden Badge of Wrocław University of Technology, Medal of the Commission of National Education and Silver and Gold Cross of Merit, Order of Rebirth of Poland. He is doctor honoris causa of Lviv Polytechnic National University, honorary professor of Obuda University. Currently he is rector of Wrocław University of Technology.

E-mail: Tadeusz.Wieckowski@pwr.wroc.pl
Institute of Telecommunications and Acoustics
Wrocław University of Technology
Wybrzeże Wyspiańskiego st 27
50-370 Wrocław, Poland