Gyrotrons

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Gyrotrons are among the most powerful sources of coherent radiation that operate in CW and long pulse regimes in the sub-THz and the THz frequency ranges of the electromagnetic spectrum, i.e. between 0.3 THz and 3.0 THz (corresponding to wavelengths from 1.0 to 0.1 mm). This region, which spans between the frequency bands occupied by various electronic and photonic devices, respectively, is habitually called a THz power gap. The underlying mechanism of the operation of the gyrotron involves a formation of bunches of electrons gyrating in a helical electron beam and their synchronous interaction with a fast (i.e. having a superluminal phase velocity) electromagnetic wave, producing a bremsstrahlung radiation. In contrast to the slow-wave tubes, which utilize tiny structures with dimensions comparable to the wavelength of the radiation, the gyrotrons have a simpler resonant system (cavity resonator) with dimensions that are much greater than the wavelength. This allows much more powerful electron beams to be used and thus higher output powers to be achieved. Although in comparison with the classical microwave tubes the 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 in a sophisticated laboratory equipment (e.g. spectrometers, technological systems, *etc.*) than other devices such as free-electron lasers (FEL) and radiation sources based on electron accelerators. Nowadays, the gyrotrons are used as powerful sources of coherent radiation in the wide fields of high-power sub-THz and THz science and technologies [1][2][3].

Keywords: gyrotrons ; THz waves ; coherent radiation sources ; sub-millimeter waves

1. Introduction

The recent years are witnessing remarkable progress and the proliferation of various applications that are utilizing electromagnetic radiation with terahertz frequencies belonging to the so-called terahertz (THz) gap, which nowadays is more frequently referred to as the last frontier of the electromagnetic spectrum. This is stipulated by the unique properties of the THz waves, which are also known as THz rays (for an insightful comment on the legitimacy and the subtle distinctions of the usages of these two terms, see [4]). Among them, the following characteristics are the most notable. First, the terahertz radiation is invisible by a naked human eye, but it penetrates dielectric materials (e.g., plastics, paper, textile, wood) that are opaque in the visible range of the spectrum. At the same time, it is strongly absorbed by water and other polar liquids (solvents) but compared with visible and IR light is less affected by attenuation due to both Mie and Rayleigh scattering because of the significantly longer wavelength. Moreover, the terahertz waves are non-ionizing (in contrast to extreme-UV light and X-rays), non-invasive, non-destructive, and therefore biologically safe and harmless at low specific absorption rates. An even more important feature of the THz waves stems from the fact that their frequencies correspond to the characteristic frequencies (resonances) of the molecular motions (rotations, vibrations, stretching, hybrid modes of motion), and the irradiation of various gases and organic substances produces specific signatures that can be observed analyzing the resulting transmission, absorption, and reflection spectra. This allows using the THz waves for detecting/sensing many substances that exhibit such characteristic spectra. The basic mechanisms of such interactions are now well understood [5][6][7], and their underlying theoretical interpretations serve as a basis for the development of a wide range of methods and techniques [5][8] in material spectroscopy [9], bio-sensing [10][11][12][13], pharmaceutical industry [14], food inspection [15][16], and security [17].

The main components of any THz system that determine its operational performance are the used radiation sources [5][18] and detectors [19]. The terahertz region, a kind of “no man's land”, which borders the microwaves and light and thus the domains occupied by the electronic and photonic devices, respectively, is nowadays being populated by various sources coming from both sides (“borders”) of this frequency range. It is believed that such convergence would finally lead to filling (bridging) the gap. The clear aims in such direction have been seen well in the recently formulated THz science and technology roadmap [20]. Despite the progress demonstrated by practically all radiation sources, there is a noticeable difference in their output power levels. Although sufficient for many applications, the power of the most frequently used solid-state devices (e.g., IMPATT and Gunn diodes, quantum cascade lasers (QCLs) that are tunable in a wide frequency range) is orders of magnitude lower than that provided by the vacuum tubes (initially mm-wave sources that recently advanced toward the THz frequencies) such as Backward Wave Oscillators (BWO), and accelerator-based electron-beam sources [21] (most notably the Free Electron Lasers (FEL) and storage rings). A conventional figure of merit that characterizes the latter devices, as well as the high-power microwave tubes, is given by the product of the average output power p and the frequency f squared (pf^2). With respect to this value, the gyrotrons are among the most powerful sources of both pulsed and CW (continuous wave) coherent radiation in the terahertz frequency range and recently are contributing significantly to bridging the THz gap, providing terahertz waves for different applications in the fundamental scientific research and the technologies [22][23]. Some of them are well established (for example, the ECRH (electron cyclotron resonance heating) of fusion plasma, materials treatment, radars), while others have been born recently or are currently emerging. The latter include various advanced spectroscopic techniques such as for instance electron spin resonance (ESR), nuclear magnetic resonance with signal enhancement through dynamic nuclear polarization, (NMR-DNP), plasma physics studies, and novel medical technologies. The current state-of-the-art of the development and application of gyrotrons is well represented in the annually updated report [24] as well as in numerous recent review papers (see for example [25][26][27][28][29]). Here, our overview is focused on the potential of the gyrotrons as appropriate and versatile radiation sources for imaging and sensing.

2. Advantages of the Gyrotrons as Powerful Radiation Sources for Sensing and Imaging

The gyrotrons are vacuum electron tubes that belong to the family of gyro-devices, of which other prominent members are the Gyro-Klystrons, Gyro-TWT (Traveling-Wave Tubes), Gyro-BWO (Backward-Wave Oscillators), and CARM (Cyclotron Autoresonance Masers). All of these utilize hollow electron beams in which the electrons follow helical orbits gyrating with a cyclotron frequency Ωc in a strong magnetic field B

$$\Omega_c = \frac{e}{\gamma m_0} B,$$

where e and m0 are the charge and the rest mass of an electron, respectively, and $\gamma = (1 - \beta^2)^{-1/2}$ is the relativistic Lorentz factor ($\beta = v/c$ being the electrons' velocity normalized to the speed of light in vacuum c). The operation of the gyro-devices is based on a physical phenomenon known as electron cyclotron maser instability, which takes place due to the relativistic dependence of the cyclotron frequency on the energy of the gyrating electrons provided a proper synchronism between the electron beam and the electromagnetic wave excited in the resonant cavity (usually a part of a cylindrical waveguide) is established in accordance with the following relations

$$\omega = n\Omega_c + v_z k_z,$$

$$\omega^2 = c^2 \left({k_\perp}^2 + {k_z}^2\right),$$

where ω is the circular frequency of the electromagnetic wave, n is the harmonic number of the cyclotron resonance, vz is the axial component of the velocity of the electrons, and k⊥ and kz are the transverse and the axial wave-numbers of the cavity mode, respectively. Therefore, the resonance condition (synchronization) can be conveniently presented graphically as an operation point at the intersection of the beam line (2) and the dispersion curve (3) of the corresponding cavity mode as shown on the Brillouine diagram in Figure 1.

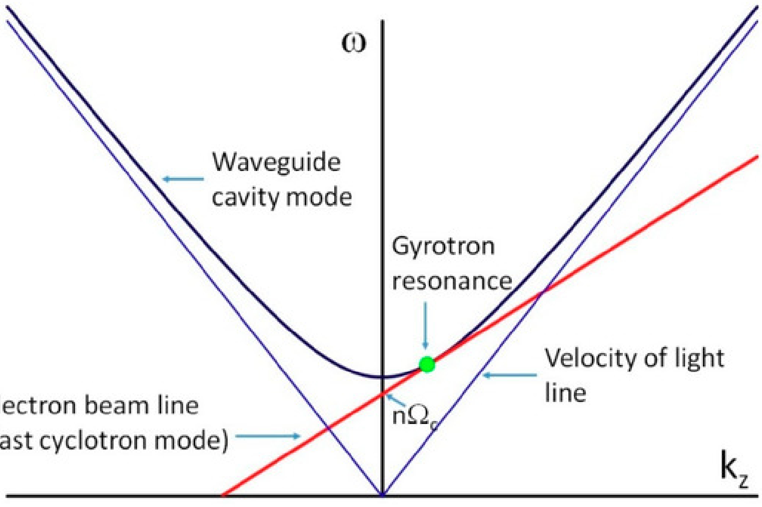

Figure 1. Gyrotron interaction illustrated by the Brillouine diagram.

Both the frequency and amplitude modulations are essential for many applications, such as for example in the remote sensing of atmosphere, communications, advanced diagnostic and spectroscopic techniques, etc. Recently, it has been demonstrated that the signal enhancement in the DNP-NMR spectroscopy can be increased significantly by using frequency-modulated CW radiation [30][31][32]. In the gyrotrons, the mechanism of frequency modulation is based on the relativistic dependence of the cyclotron frequency on the energy of the electrons (as it has been explained by Equation (1)) and is being realized by alternating the body potential of the tube and therefore by varying the accelerating voltage [33]. Although the variation of the frequency $\Delta f \leq f/2Q$ is limited by the quality factor Q of the resonator, a modulation depth sufficient for many practical purposes can be obtained. A good example of a radiation source with such capabilities is the 0.46 THz gyrotron FU CW GVI (developed at FIR UF and used in the 700-MHz DNP-NMR spectrometer at the Osaka University under the name Gyrotron FU CW GOI) [34]. It has the following modulation characteristics, which are appropriate for this particular measuring system but more generally illustrate this eminent feature and advantage of the gyrotrons. A modulation amplitude of up to ±50 MHz is obtained with the cavity potential variation of ±0.5 kV with a modulation frequency of 300 Hz. In these experiments, both sinusoidal and triangular modulations of the beam voltage have been used. At some modulating parameters (frequency and amplitude of the modulating signal), a linear dependence of the frequency variation on the voltage variation has been observed. Analogously, by sweeping the anode voltage in a frequency tunable 0.26 THz gyrotron and sweep rates up to 14 kHz, a 60% gain in the signal enhancement has been observed [34].

3. Illustrative Applications of Gyrotrons to Advanced Spectroscopic Techniques, Imaging, and Inspection

3.1. Advanced Spectroscopic Techniques

The spectroscopy based on nuclear magnetic resonance (NMR) is a powerful and widely used method for studying a big variety of compounds (e.g., complex biomolecules such as proteins) in biomolecular research, material, and pharmaceutical sciences. However, its main drawbacks are low sensitivity, low signal-to-noise ratio, and, respectively, long spectrum acquisition times. A technique developed at MIT [35] for enhancement of the NMR signal through a dynamic nuclear polarization has radically solved these problems. It involves adding a polarizing agent to the sample, irradiation by gyrotron radiation, and transferring the polarization of the unpaired electron spins to the neighboring nuclear spins. In other words, DNP-NMR is a combination of two techniques, namely electron paramagnetic resonance (EPR), aka electron spin resonance (ESR), and NMR, which provides a significant (theoretically, up to several orders of magnitude) increase of the sensitivity and decrease of the acquisition time. After the pioneering breakthrough [35], a series of gyrotrons for DNP-NMR spectroscopy have been developed at MIT [27], where the first 140 GHz system has been followed by a series of spectrometers utilizing gyrotrons with output frequencies of 250, 330, and 460 GHz and operating at the second harmonics of the corresponding cyclotron resonances. For coupling of the gyrotron radiation to the sample, low loss transmission lines are being used. For application in the time-domain DNP-NMR techniques, two gyro-amplifiers operating at 140 GHz and 250 GHz, respectively, have been developed as well.

The positronium is a metastable bound state of one electron and a positron that forms an exotic hydrogen-like atom. It can exist in two states, namely ortho-positronium (o-Ps) and para-positronium (p-Ps). The energy splitting between o-Ps and p-Ps, i.e., the HFS is about 203.4 GHz. A significant discrepancy of 3.9 standard deviations between the measured HFS values and the theoretical prediction of the quantum electrodynamics (QED) motivated the development of a novel method for the direct and precise evaluation of HFS [36]. In contrast to the previous indirect methods (e.g., measuring the Zeeman splitting in a static magnetic field) that are prone to systematic errors, the new approach relies on a stimulated transition between o-Ps and p-Ps states induced by irradiation with a strong electromagnetic wave with a frequency of about 203 GHz generated by a gyrotron. The experimental setup includes a transmission line that delivers and couples the wave beam to a high-finesse Fabry-Pérot (FP) cavity in which a power of about 10 kW is accumulated, and it includes a gas chamber and a positron source as well as a set of detectors and an electronic control system. The positronium is formed in the cavity using a 22Na source of positrons and nitrogen mixed by iso-butane as a stopping target. Under the irradiation by a 203 GHz wave, some of the o-Ps (decaying into three photons) transit into p-Ps (decaying into two photons), and consequently, the ratio of two-photon events increases. This process is monitored by the photon detectors (LaBr3(Ce) scintillators) that are located around the cavity. In the measurements, the frequency of the gyrotron is varied within approximately 2 GHz in order to observe a Bret–Wigner resonance of the transition. The hyperfine transition has been observed with a significance of 5.4 standard deviations. The transition probability that has been measured directly for the first time is found to be $A=3.1 \pm 1.61.2 \times 10^{-8}\ s^{-1}$, which is in a good agreement with the theoretical value of 3.37 ×

10^{-8} s^{-1} [37]. Recently, the whole Breit–Wigner resonance of the transition from o-Ps to p-Ps has been measured for the first time using a frequency-tunable millimeter-wave system and tuning the gyrotron in a very wide range from 201 to 205 GHz by changing successively several gyrotron cavities of different radii.

The XDMR spectroscopy is a new and unique element- and edge-selective technique [38] which allows to resolve and study the precession dynamics of spin and local orbital magnetization components. In this Pump&Probe technique, the X-ray magnetic circular dichroism (XMCD) is used to probe the resonant precession of the magnetization produced by the irradiation with a strong microwave pump wave applied perpendicularly to the static magnetic field. The utilization of gyrotrons as powerful pump sources allows to extend this technique to the sub-THz frequency range and, respectively, to stronger magnetic fields. The first proof-of-principle feasibility study on the sub-THz XDMR spectroscopy has been conducted at the European Synchrotron Radiation Facility using a refurbished version of the gyrotron FU II which was operated at 76 and 138 GHz (fundamental resonances of the TE011 and TE021 modes, respectively). It is anticipated that this promising spectroscopic technique can be used for investigation of various electro-optical and magneto-electric effects, including the dynamics of Van Vleck orbital paramagnetism, as well as for studies on both optical and acoustic modes in ferrimagnetic and antiferromagnetic systems [39].

Nowadays, the gas molecular spectroscopy (which is, in fact, one of the earliest applications in the terahertz spectral region) is a powerful tool used in various fundamental and applied studies as, for example, qualitative and quantitative gas analysis, non-invasive medical therapies, atmospheric remote sensing, and so on. As for any other spectroscopy, sensitivity is the main issue, since this key parameter determines the accuracy of the measurements and eventually the scope of the problems to which this technique can be applied. The current levels of the achieved sensitivity in the conventional schemes of mm-wave spectrometers have already approached the physical limits. The only known method for further increase of the sensitivity is based on the opto-acoustic (aka photo- or radioacoustic) detection of absorption. In this method, the result of the interaction of the radiation with matter is detected rather than the radiation itself. An efficient approach for increasing the sensitivity of the radioacoustic detection (RAD) by increasing the power of the radiation source has been realized in an automated facility [45]. As a radiation source, it uses a gyrotron developed at IAP-RAS and operated in CW regime at a frequency of about 263 GHz (which can be tuned continuously within an interval of 0.2 GHz by varying the electron beam voltage and the temperature of the cavity) with an output power of up to 1 kW. The width of its radiation spectrum Δf is about 0.5 MHz ($\Delta f/f \sim 10^{-6}$) and is determined by the fluctuations of the accelerating potential instabilities of the accelerating potential provided by the high-voltage power supply. Recently, the capabilities of the RAD spectrometer have been demonstrated using as a test gas sulfur dioxide (SO_2), which has a very dense and a well-studied spectrum in the mm/sub-mm range. It has been estimated that the maximum absorption sensitivity of the spectrometer is of the order of 6×10^{-10} cm^{-1}. The bottom line of these experiments is that an increase in the scanning radiation power by about three orders of magnitude leads to a proportional increase in the sensitivity of the RAD spectrometer [40]. This result clearly proves the efficiency of the outlined “power” approach and suggests some direction for a further realization of its potential; however, this is limited by the spectral line saturation effect. The latter problem can be substantially reduced by proper selection of the molecule, the transition, and experimental conditions. It is believed that through combining this method with complementary conventional techniques (e.g., increasing the optical path), a record-breaking sensitivity can be achieved.

3.2. Remote Atmosphere Sensing Using Gyrotrons

The gyrotrons have demonstrated their potential as radiation sources for the remote sensing of clouds in the atmospheric window at 94 GHz (where the Rayleigh scattering from the droplets in the cloud have a cross-section that is proportional to λ−4) a long time ago [41]. Ground-based radiometry in this frequency range has been extremely useful in detecting upper-atmosphere trace elements [41]. Nowadays, the Gyro-TWA (Gyrotron Travelling Wave Amplifiers) are considered as even more appropriate, as they offer a 10-fold increase in the available bandwidth and a fivefold increase in the peak power over the amplifiers used in the current cloud profiling radars. It is expected that this will lead to a significant increase of the radar sensitivity, enabling the detection of smaller particulates, with higher resolution, at both longer ranges and shorter timescales. The technology also has the potential to be applied to the ground-based mapping of space debris, which is a major consideration for all orbiting systems, including environmental monitoring satellites [42]. A novel W-band Gyro-TWA for cloud radar applications developed at the University of Strathclyde is based on a helically corrugated resonant structure and utilizes an axis-encircling (aka uniaxial) electron beam formed in an electron-optical system with a cusp electron gun. This tube can provide a maximum power of 5 kW at its center frequency of approximately 94 GHz with an instantaneous frequency bandwidth of 10 GHz operating at a high pulse repetition frequency of 2 kHz [43].

3.3. Remote Detection of Concealed Radioactive Materials

Recently, a new scheme for detecting concealed sources of ionizing radiation by observing the occurrence of a localized breakdown in atmospheric air produced by a focused electromagnetic wave whose electric field intensity surpasses the breakdown field in a small volume surrounding the radioactive material has been proposed [44]. The principle of this promising method stems from the fact that any radioactive material emits gamma rays, which ionize the surrounding air and thus produce free electrons. In this technique, the chosen volume (with dimensions on the order of a wavelength) is smaller than that of the naturally occurring free electrons. Since in the absence of radioactive materials, the ambient electron density is very low, the probability of finding a free electron that could trigger an avalanche breakdown process is such a small volume is also negligible. Therefore, observing a breakdown there indicates a presence of hidden radioactive material in the vicinity of the focused wave beam. Another specific requirement is that the pulse length of the electromagnetic wave "must exceed the avalanche breakdown time of approximately 10–200 ns and could profitably be as long as the statistical lag time in ambient air (typically, microseconds)" [44]. The analysis of the potential sources in the wavelength range 3 mm > λ > 10.6 μm has revealed that the most appropriate would be a 0.67 THz gyrotron oscillator with an output power of 200 kW and pulse duration of 10 μs or a Transversely Excited Atmospheric-Pressure (TEA) CO_2 laser with 30 MW, 100 ns output pulses. The estimates presented in the cited analysis show that a system employing a 670 GHz gyrotron would have superior sensitivity, while a similar realization based on the TEA CO_2 laser could have a longer range of up to 100 m.

3.4. Imaging, Food Inspection, and Quality Control Using Gyrotron Radiation

Many industrial processes, most notably food production and processing due to their importance, the large volume of products, numerous serious safety, and quality control concerns could benefit enormously from non-destructive screening and inspection. Such a perspective has stimulated the development of various novel THz technologies [46][47][48] that avoid the usage of ionizing radiation (X-rays), which has a detrimental effect on the living matter. However, most of the techniques utilize broadband THz radiation (e.g., TDS (time-domain spectroscopy) systems) or laser light of low power and higher frequencies that, respectively, have small penetration depth. In this respect, the gyrotron radiation (with its sub-THz and THz frequencies and several orders of magnitude higher output powers) offers complementary/alternative solutions. Although these advantages have not been fully realized so far, a series of recent investigations have demonstrated the potential of the systems for food inspection and control based on imaging with gyrotrons [15][49][50][51][52][53].

3.5. Active Thermal Imaging Using Gyrotrons

Another technique that benefits from the high-output power of the sub-THz gyrotrons is the long-range sensing based on active thermal imaging [54][55]. Its principle is grounded on the fact that when beamed on the target, the millimeter-wave gyrotron radiation generates rapid transient temperature increases in different portions of the irradiated area. The time-dependent thermal field is registered using sensitive infrared (IR) imagers. In principle, this concept can be used in many situations where passive infrared imaging is currently used. The preliminary laboratory proof-of-principle experiments have demonstrated its feasibility [55]. In the measurements, an 83 GHz gyrotron with an output power of 20 kW has been used to rapidly heat various simple and complex targets. Thermal imaging with a sensitive mid-wavelength IR camera reveals clear signatures in a variety of objects illuminated at power levels of 50–200 W over an area of approximately 100 cm^2. In these experiments, the target was located 1.6 m from the source, while the IR camera was located 1.2 m from the target. A variety of objects and configurations, including obscured metallic and dielectric specimens buried in sand, and covered by several layers of cloth have been detected successfully. Since temperature differences of a few hundredths of a degree can be detected, temperature changes are often visible almost immediately after the irradiation [56]. Among the anticipated potential applications is a long-range detection of explosive devices. The comparison of similar systems for active thermal imaging that use a variety of heating sources (e.g., lasers, flashlamps, and longer wavelength microwaves) shows that the millimeter-length waves provided by the sub-THz gyrotrons are particularly well suited for long-range sensing.

3.6. A High-Sensitivity Technique for Time-Resolved Imaging and Measurement of 2D Intensity Profiles of Millimeter-Wave Radiation

Recently, a novel high-sensitivity time-resolved method for imaging and measuring the spatial distribution of the intensity of millimeter waves by using visible continuum emitted by the positive column of a DC gas discharge in a mixture of cesium vapor with xenon has been proposed and demonstrated experimentally [57][58]. This imaging technique can be used for measuring the parameters of moderate-power radiation generated by various sources of millimeter waves and has been applied to the identification of the operating mode of a W-band gyrotron with a pulsed magnet as well as to the evaluation of the relative powers of some spurious modes. It has been shown also that this method can be applied to real-time imaging and non-destructive testing with a frame rate higher than 10 fps. In the experiments, two-dimensional shadow projection images of objects opaque and transparent to millimeter waves have been obtained irradiating the studied objects with pulsed watt-level millimeter waves. Moreover, it has been demonstrated that this particular type of shadowgraphy can be used for both single-shot screening (e.g., detection of concealed objects) and time-resolved imaging of time-dependent processes.

4. Conclution

Nowadays, we are witnessing spectacular progress in the broad fields of the terahertz science and technology stipulated by the remarkable advancements in the development of the fundamental triad: sources, detectors, and methods. Each of them stimulates both the improvement and further evolution of the other two, and together, these three basics generate a synergy effect leading to the emergence of novel devices, methods, and applications. As the most powerful sources of coherent radiation in the sub-THz and THz frequency range operating in both pulsed and CW regimes, the gyrotrons have demonstrated a remarkable potential for bridging the so-called THz gap and have opened the road to many novel applications in the fundamental physics research and applied sciences. In this review, the advantages of the gyrotrons as versatile radiation sources have been presented and illustrated with an emphasis on some of the most notable and well established as well as emerging technologies. The selected examples reveal both the current state-of-the-art of their development and bring to light the main trends for further improvements in their operational performance and functionality.

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