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T. Idehara, T. Saito, I. Ogawa, S. Mitsudo, Y. Tatematsu, S. Sabchevski

Research Center for Development of Far-Infrared Region
University of Fukui

Bunkyo 3-9-1, Fukui 910-8507, Japan

Tel 81 776 27 8657
Fax 81 776 27 8770
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T. Idehara¹, T. Saito¹, I. Ogawa¹, S. Mitsudo¹, Y. Tatematsu¹, S. Sabchevski¹,²

¹Research Center for Development of Far Infrared Region
University of Fukui, 3-9-1 Bunkyo, 910-8507 Fukui, Japan

²Institute of Electronics of the Bulgarian Academy of Sciences,
1784 Sofia, Bulgaria

Abstract:

Coherent sources of radiation in the spectral region between the microwaves and the optical waves are necessary for an increasing number of applications in the fundamental research and in the technologies. Many classical electronic and photonic devices as well as some recently developed terahertz emitters can generate in this actively developed spectral range but are limited to low output powers. The most powerful devices that have the potential to bridge the power gap (THz-gap) in the electromagnetic spectrum are the gyrotrons, also known as Electron Cyclotron Resonance Masers (ECRM). They are characterized by many advantageous features, e.g. step-like broadband and continuous narrow-band tunability, possibility to modulate the amplitude and the frequency of the radiation, high mode purity, short-, long-pulse and CW stable operation etc.

In this FIR Center Report we review briefly the state-of-the-art of the gyrotrons, discuss the recent advancements in the development of high frequency gyrotrons generating coherent radiation in the sub-terahertz and the terahertz regions of the electromagnetic spectrum and compare them with other devices. We shortly summarize the known applications of such sources and review their potential for usage in novel fields taking into account their advantages but also the known physical and technical limitations. We also provide illustrative examples using the results of the theoretical and experimental investigations carried out at the Research Center for Development of Far-Infrared Region using the developed there millimeter and submillimeter wave gyrotrons.

Key words: sources of coherent radiation, gyrotrons, sub-terahertz, terahertz, T-waves, T-gap, terahertz technologies
1. Introduction

Practically all material objects emit electromagnetic waves with continuous spectrum ("black-body" or thermal radiation) with a peak which intensity and position depend on their temperature according to the Wien’s law and the Stephen-Boltzmann’s law, accordingly. Although most of such radiation in the universe since the Big Bang is in the terahertz frequency band, the frequency range situated between the microwaves and the optical waves (i.e. between electronics and photonics) is usually considered as a gap (THz-gap or T-gap) in the electromagnetic spectrum due to the lack of coherent sources and detectors in this intermediate region (aka far-infrared region). The radiation at sub-terahertz and terahertz frequencies, i.e. between 0.3 THz and 3 THz, corresponding to wavelengths from 1.0 to 0.1 mm is called T-rays, T-light or T-waves.

Like infrared radiation or microwaves, these waves usually travel in line of sight. The THz rays are non-ionizing due to the small energy of the photon (1 THz = 0.41 meV) and share with microwaves the capability to penetrate a wide variety of non-polar dielectric materials (e.g. textiles, leather, paper, wood, plastic, ceramics etc.) with moderate attenuation as well as fog and clouds but cannot penetrate metals and water. This makes them a perfect probe for non-invasive and non-destructive inspection using various spectroscopic and imaging techniques. This is a radiation, which can be focused (unlike the X-rays) and steered easily than the microwaves by quasi-optical mirrors with greater spatial resolution.

The specific interaction of the THz radiation with different substances opens up new perspectives for a large number of applications in measurement technology. From GHz to THz frequencies, numerous organic molecules exhibit strong absorption and dispersion due to rotational and vibrational transitions. These transitions are specific to the targets and enable T-ray fingerprinting. Many biological molecules exhibit vibrational modes corresponding to collective molecular oscillations, unfolding of molecular subdomains, twisting and
deformation of the double-helix structure in DNA etc. that can be probed directly by THz radiation. The sub-THz and THz frequencies fall also in the spectral range which is characteristic for the behavior of the subatomic systems (e.g. electron spin systems). This makes the THz waves appropriate radiation for various pump and probe and spectroscopic techniques like electron spin resonance (ESR) and nuclear magnetic resonance (NMR) spectroscopy.

The unique characteristics of the sub-THz and THz waves are used in a great and continuously increasing number of applications in the fundamental scientific research (physics, chemistry, structural biology), in many interdisciplinary fields (biophysics, biomimetics etc.), in radars, in the communications, in the processing technologies and in medical diagnostics and therapy [1-3]. Some of them are shown in Fig.1 together with the synergetic links between the fields related to the R&D on the THz waves. All this numerous applications produce great interest and demand for coherent radiation sources operating in the THz frequency band. Among them, the gyrotrons emerge as the most powerful devices that have demonstrated the capabilities to contribute significantly for bridging the T-gap. In this paper we discuss their potential for development of some traditional but also novel fields of application comparing it with the capabilities of other electronic and photonic devices.

2. Sources of sub-THz and THz radiation and their limitations

The fact that the THz radiation is in the transition region between electronics and photonics has led to trials to bridge the THz gap by both photonic and electronic devices with quite different and widely varying output characteristics [4-6]. The radiation sources operating in the sub-THz and THz frequency regions can be divided in four main classes, namely free electron vacuum devices, solid-state electron devices, lasers and laser driven THz emitters. The first one is represented by three groups of tubes, namely the conventional slow wave tubes (Cherenkov devices), fast wave devices and,
accelerator-based sources. The second class includes solid-state oscillators such as Gunn and IMPATT diodes and Schottky diode multipliers [4]. The third class encompasses such as Gunn and IMPATT diodes and Schottky diode multipliers [4].

Fig. 1 Fields of application of the THz waves and the synergy between them

class encompasses the Far Infrared (FIR) gas laser and the quantum cascade laser (QCL) [7] that are the oldest and the newest coherent sources developed for this spectral range, respectively. The laser driven THz emitters are based on frequency down-conversion from the optical region. Among their representatives the most widely used is one based on a short pulse (femtosecond) Ti:Saphire laser, which illuminates the gap between two closely spaced electrons on a photoconductor (for example Si on Saphire or GaAs) creating carriers which are accelerated by the bias voltage applied to the electrodes. The resulting transient
current generates electromagnetic field in a wide band at terahertz frequencies corresponding to the Fourier transform of the time profile of the laser pulse.

For the current state-of-the-art achieved by these devices we refer the reader to the above cited review papers. Here we will only briefly summarize the ultimate capabilities from the point of view of the output power and frequency (which are most notably described by such figure of merit as $Pf^2$, i.e. output power times frequency squared) and the limitations characteristic for them [5]. The reason for the existence of the T-gap is that most of the electronic devices generating microwave radiation face both physical and technical limitations approaching the millimeter and submillimeter wavelength regions. For example, the well-known scaling relations limit the increase of the frequency of the conventional microwave vacuum tubes since (i) the linear dimensions scale as $\propto 1/f$, (ii) the ohmic loses in the skin depth as $\propto f^{1/2}$, (iii) the required beam current density as $\propto f^{5/2}$, and (iv) the heat dissipation per unit volume as $\propto f^{7/2}$ [8]. Despite these limitations, recently a steady progress toward higher frequencies has been demonstrated by such classic linear beam devices as traveling wave tubes (TWT), backward wave oscillators (BWO) and klystrons based on improved and innovative designs. The current state-of-the-art is well represented by the latest commercially available devices. For example, the leading manufacturers of TWT, CPI and Thales produce Ka-band (18-40 GHz) helix TWT with output power 40-60 W. The BWO can deliver radiation at much higher frequencies but at lower output power levels. For instance, the output powers of a series of oscillators produced by MICROTECH Instruments are 10-100 mW for the frequency range 100-180 GHz, and 0.2-0.5 mW for the frequency range 1.2-1.42 THz. Another device which extends the operation of the conventional tubes into the THz region is the Extended Interaction Klystron (EIK). CPI offers EIK delivering 50 W pulsed power and 6 W average power at 220 GHz and 30 W (0.3 W average) at 280 GHz. Preliminary analysis indicates that EIK operation at 700 GHz could deliver 2 W pulsed power and 0.1 W average power. It is believed that the success with novel technologies such as multiple or sheet beams, cold cathodes, lithographic manufacturing etc. will
further expand EIK performance and frequencies but it is clear that the higher the frequency the lower will be the output power.

It is well known that according to the fundamental theorem on the maximum frequency of coherent electron beam oscillations formulated by R.S. Elliot [9] these devices cannot generate in the terahertz spectrum and can only reach its far-infrared frontier. Therefore, one has to admit that the conventional devices (despite their high level of sophistication and maturity) have almost reached the limiting frontier of the frequency increase at least at appreciable output power levels.

It should be mentioned that the microwave sources based on the stimulated Smith-Pursell radiation (e.g. Orotron [10]) are very attractive (especially for the submillimeter wave spectroscopy) because of their broad frequency tunability, low operating voltage and compact size. Although the orotrons can produce higher output power than the BWO's they remain low power devices. In the frequency range of 0.1-0.4 THz the maximum output power is 1.0-0.1 W.

The solid-state devices are limited in frequency due to both to the transit time of the carriers and resistance–capacitance effects, which causes high frequency roll-off. Currently a variety of solid-state sources operate in CW mode at room temperature in the millimeter region of the spectrum with varying output powers and bandwidths. For instance, the Gunn oscillators made from GaAs, InP, and GaN, are available at frequencies of up to 140 GHz in the InP version and may serve as oscillators in the THz region. The output power falls as $1/f^2$ or even as $1/f^3$ for frequencies above 100 GHz [4]. Typical levels of the output power are around few milliwatts but for frequencies above 1 THz they are even below the milliwatt level. This fundamental limitation applies also to the solid-state frequency multipliers, which are used to reach the region above 200 GHz, up to about 1 THz. For such devices the average output power is in the interval between 0.1 and 1 mW around 400 GHz.

In the QCL a series of thin layers of varying material composition (heterostructures) form a super lattice, which introduces a varying electric
potential that can be considered as a series of quantum wells. The amplification is obtained by a stimulated emission of electrons passing between quantized sub-bands in two dimensional quantum wells [7]. At present, the frequency range covered by these devices is from 0.84 to 5.0 THz at temperatures up to 169 K in a pulsed regime and 117 K in a CW regime. The maximum output powers are around 250 mW.

Optically-pumped lasers (OPLs) deliver both CW and pulsed radiation within the sub-terahertz and terahertz bands at discrete frequencies. They comprise some sort of gas cell (e.g. methanol) at pressures in the mbar range, which is the active lasing medium, that is pumped by a CO$_2$ laser. These devices are inherently inefficient because the pump laser excites the active medium into a higher vibrational state, and the laser transitions occur between rotational levels within this state, which have several orders of magnitude lower energy. A typical output power of methanol laser at the line with wavelength 118 $\mu$m is around 100 mW. Additional limitations come from the fact that they operate only on discrete frequencies (i.e. they are line-tunable in the range 0.3 to 5 THz) and their pulsed versions have low duty cycle.

The free electron lasers (FEL) use relativistic electron beams propagated through a periodic structure of magnets, called insertion devices (wigglers or undulators). They generate radiation over a broad spectrum from the submillimeter wave to the x-ray region. As an illustration for the performance of the THz FEL we will present the radiation parameters of one such laser, namely of one which is based on an accelerator-recuperator (energy recovery linac). It can be tune for operation on a wavelength from 0.12 to 0.18 mm. The pulse has a length of 0.05 ns, a peak power of 0.6 MW, a repetition rate of 5.6 MHz and an average power of 0.2 kW [11]. Usually the FEL systems are extremely expensive, large and are placed in a complicated permanent infrastructure. At the same time there is a tendency for development of compact FEL and Table Top Free electron Radiators [4]. Such laboratory scale user facility operates in the wavelength range of 0.1 to 1.2 mm, which corresponds to the frequency of 0.3-3 THz [12]. The peak power is of the order of 1 kW.
Another approach pioneered at Jefferson Lab (Jlab) is based on the use of small bunches of electrons (all contained within a THz wavelength) produced by a photo-injected energy recovered (superconducting) linear accelerator [6,13]. When deflected by magnetic field these electrons radiate according to the relativistic Larmor formula (synchrotron radiation). In these experiments however the synchrotron radiation is not produced from an electron storage ring as is usual for the synchrotron facilities worldwide. In the storage rings electrons spread out due to mutual repulsion to form bunches that are typically several cm long. In the Jlab source each bunch circulates just once, so the tight bunch of electrons does not have time to spread out significantly. As such the electric field created by passage of this bunch is in phase for each electron, i.e. the fields add coherently so that the intensity of the radiation scales as squared number of electrons, \( N^2 \). This enhancement is very large since the number of electrons in the bunch is typically of the order of \( 10^9 \). In [14] also short electron bunches are used but they radiate in a standard undulator. Another difference is that the bunches are formed recirculating an electron beam through a high gradient superconducting RF cavity.

3. Gyrotrons – the current state-of-the-art and the potential for future

The gyrotrons (aka electron cyclotron masers) are fast-wave inherently relativistic vacuum electron tubes that generate coherent radiation in a broad frequency range [15]. The principle of their operation is based on the resonance between the cyclotron motion (gyration) of the electrons in a strong magnetic field \( B_0 \) and the Doppler shifted frequency of the electromagnetic field in a resonant cavity. This resonance gives rise to the so-called electron cyclotron maser instability, which results from the dependence of the electron cyclotron frequency \( \Omega_c = eB_0 / \gamma m_0 \) (where \( e \) and \( m_0 \) are the charge and mass of an electron) on the electron’s energy through the relativistic factor \( \gamma \). Provided that the Doppler shifted radiation frequency is slightly higher that \( \Omega_c \) (or its harmonics \( n\Omega_c \), where \( n \) is the harmonic number) the electrons experience azimuthal phase
bunching and the formed bunches slip naturally into decelerating phase where they transfer some of their transverse energy to the wave through a bremsstrahlung interaction. Usually the gyrotrons utilize weakly relativistic helical electron beams with energy less than 100 keV ($\gamma < 1.2$) in which the ratio of the transverse and axial velocity (so called pitch factor or velocity ratio) is of the order of 1.3-1.5. This means that the bigger portion of the energy of an electron is related to its transverse motion. This is essential since only the transverse energy of the electrons can be extracted through the above-mentioned mechanism. Another specific feature of the gyrotrons is that the wave vector of the radiation in the cavity resonator is small (since the wave is almost transverse to the external magnetic field) which gives negligible Doppler shift (for mildly relativistic electrons). As a result, the frequency of the generated radiation is close to $n\Omega_c$, i.e. it is determined by the applied magnetic field strength.

In contrast to the slow wave devices, the coupling between the electron beam and the microwave radiation in the gyrotrons allows the beam and the microwave circuit dimensions to be large compared to the wavelength so that one can increase considerably the beam power, use higher order transverse modes and alleviate the problems with the thermal loading. In fast-wave circuits the electric field strength can be quite high, regardless of the proximity of the metallic walls of the cavity. This enables the electron beam to be situated in regions of strong electric field without placing it close to delicate structures. All these advantageous features of the gyrotrons are favorable for significant advancement towards highest output powers. The gyrotrons are the most powerful sources of coherent radiation in the millimeter and submillimeter wavelength regions of the electromagnetic spectrum and are characterized by the highest value of the $Pf^2$ quality factor, where $P$ and $f$ are the output power and the frequency, respectively (see Fig. 2). In this respect the gyrotrons demonstrate great potential and offer unprecedented capabilities to close the power gap in the sub-terahertz and the terahertz regions.

The latest powerful gyrotrons for fusion research (electron cyclotron resonance heating of magnetically confined plasmas and electron cyclotron
Fig. 2 State-of-the-art of the gyrotrons. Data from [16] presented as a chart of the quality factor $Pf^2$ ($P$ - output power, $f$ - frequency of the radiation) and the lines of constant power for various devices: 1) Gyrotrons for ECRH 28-95 GHz and lower hybrid current drive 5-8 GHz of fusion plasmas; 2,3) High frequency gyrotrons for ECRH and stability control: $100 \text{ GHz} \leq f < 140 \text{ GHz}$, $\tau \geq 0.1 \text{ ms}$ 2), and $f \geq 140 \text{ GHz}$, $\tau \geq 0.1 \text{ ms}$, 3); 4) Short pulse ($3 \mu s - 15 \text{ ms}$) coaxial cavity gyrotrons; 5) Gyrotrons with conventional cylindrical or quasi-optical cavity and single-stage depressed collector (SDC) ($\tau \geq 10 \mu s$); 6) Step-tunable conventional cavity 1 MW gyrotron (FZK), multi-frequency GYCOM-N gyrotrons and three-frequency MIT gyrotron; 7) Step-tunable FZK 1 MW gyrotron with coaxial cavity; 8) Millimeter and submillimeter-wave gyrotrons operating at the second harmonic of the electron cyclotron frequency, with output power > 1 kW; 9) FIR FU large orbit gyrotron (LOG); 10) Pulsed millimeter- and submillimeter wave gyrotron oscillators operating at the fundamental electron cyclotron resonance; 11,12) Step tunable MIT’s gyrotrons (pulse length $1.5 \mu s$); 13) technological gyrotrons; 14) Relativistic gyrotrons; 15) Quasi-optical gyrotrons;
current drive in tokamaks) have already crossed the threshold of the megawatt output powers. The world record parameters of the European 140 GHz gyrotron are: 0.92 MW output power at 30 min. pulse duration and 43% efficiency, employing a single-stage depressed collector for energy recovery [16].

A maximum output power of 1.2 MW in 4.1 s pulses and of 1.5 MW in 1 s pulses [17] was generated with the JAEA-TOSHIBA 110 GHz gyrotron while the Japanese 170 GHz ITER gyrotron holds the energy world record of 2.16 GJ obtained at 0.6 MW output power level maintained during 60 min [16]. The Russian 170 GHz ITER gyrotron achieved 0.5 MW with a pulse duration of 300 s.

For a long period since 1996 and till quite recently the highest frequency achieved by a gyrotron oscillator was 889 GHz, demonstrated by the Gyrotron FU IVA at the University of Fukui [18]. The current world record belongs to the Research Center for Development of Far Infrared Region at the University of Fukui and was achieved by a pulsed gyrotron. It reached the breakthrough of 1 THz at second harmonic of the cyclotron frequency and magnetic field intensity of 19.1 T [19]. Continuing the successful development of the high frequency Gyrotron FU Series that consists of nine tubes altogether (including a Large Orbit Gyrotron, LOG) operating in pulsed regime now a novel series, namely Gyrotron FU CW, is under development. It is meant to cover sub-THz to THz range and will operate in complete CW mode. The first member of this series, FU CW I, has a 12 T cryogen-free superconducting magnet and delivers radiation with output power 1.75 kW and frequency 300 GHz [20]. The second device that belongs to the same series is FU CW II. It utilizes an 8 T liquid He free magnet and has been developed as a radiation source for NMR spectroscopy [21]. The third member, FU CW III, is in fact the second terahertz gyrotron. It is designed to reach a frequency of 1.014 THz operating continuously at the second harmonic of the cyclotron frequency and will use a 20 T superconducting magnet [22]. The next tube, FU CW IV is also developed as a radiation source for DNP-NMR
spectroscopy at 400 GHz like FU CW IIA but will have an optimized performance. It will be embedded in a 10 T cryo-free superconducting magnet and will be tunable by varying the magnetic field.

Recently, a new very compact terahertz gyrotron with a pulsed solenoid has been developed and tested at IAP-RAS [23]. At a magnetic field of 38.5 T the gyrotron generates coherent radiation at 1.022 THz in pulses of 50 µs. The output power and the energy per pulse are about 1.5 kW and 75 mJ, respectively.

Many applications require frequency tunability and precise control of the output power. The gyrotrons offer such opportunity. Fast step-like mode switching and tunability by varying the beam voltage at a constant magnetic field have been demonstrated in a great number of experiments with the gyrotrons of the Gyrotron FU Series. These devices have also achieved frequency step tunability through the altering of the magnetic field. Both a narrowband frequency tuning by varying the cyclotron frequency and a frequency modulation through modulation of the accelerating voltage of the electron beam were demonstrated too. The output power can also be modulated by varying several parameters that affect the velocity distribution of the electrons in the beam and hence the efficiency. For more details on the frequency control the reader is referred to the overview given in [24] and to the original papers cited there. Recently some new possibilities for broadband frequency tunability, based on advanced concepts have been explored as well [25].

Since the gyrotrons are voltage-controlled oscillators their frequency and output power can be stabilised using a smoothing circuit (which suppress the fluctuations of the cathode and anode potentials) together with a phase lock control. Recently, a significant improvement of the stabilization of the frequency in the Gyrotron FU IV has been reported [26]. The achieved stability is $\Delta f = 1$ KHz. This is a significant result because even for such sensitive experiments as DNP-NMR a stability of $\Delta f < 1$ MHz is satisfactory. The high mode purity is another important achievement of the high performance gyrotrons (such as FU VA [26]) which makes it easier to convert the radiation into a well collimated
Gaussian beam and to transmit it to the desired position without losses by a quasi optical system.

The gyrotrons possess a potential for further advancements towards higher frequencies. In principle, this is possible by increasing the magnetic field intensity or by operating the gyrotron at higher harmonics of the cyclotron frequency [27]. The first alternative is limited by the available cryogenic superconducting magnets. At the moment, the superconducting magnets, which have sufficient inner bore radius can produce constant magnetic fields which do not exceed 20 T. Taking into account the remarkable progress in the development of superconducting magnets based on new advanced materials (notably YBCO) one could expect devices producing fields as high as 50 T in the foreseeable future. The hybrid magnets have already reached the level of 45 T while the pulsed magnets can already produce even far higher fields [28]. All these magnets could also be used for the future gyrotron development. Unfortunately such strong magnets are rather bulky, complicated and quit expensive. This makes the second alternative more appealing. The operation of the conventional gyrotrons at higher harmonics (practically at the second and seldom at the third) however also encounters some well-known impediments. The most serious one is that the efficiency of the interaction is significantly lower than at the fundamental. Another severe problem, which is common for any operation but is much more pronounced in the case of high harmonic operation, is the mode competition. A better and more advantageous prospective is offered by another concept, namely the Large Orbit Gyrotron (LOG). It utilizes a helical electron beam in which the individual electrons follow axis-encircling orbits with a radius that is comparable with the radius of the resonant cavity. Such devices are inherently high harmonic because in them the harmonic number $n$ must be equal to the azimuthal index $m$ of the operating TE$_{mn}$ mode and in practice could be quite large. This is in fact also a stringent selection rule, which stipulates better mode selectivity and reduces the problems with mode competition. The feasibility and the potential of the LOG have been demonstrated recently by tubes developed at the FIR FU Research Center in Japan and in IAP-RAS, Russia.
[29,30]. The LOG developed at the FIR FU Center can operated on third, forth and fifth harmonics and has several important advantages. It is built using a rare earth permanent magnet and is characterized with relatively small weight and dimensions, which makes it quite portable. Since it does not need a cryogenic system the maintenance is much easier and the tube can be put in operation instantly.

4. Traditional and novel applications of gyrotron radiation

The characteristics of the gyrotrons and the current level of their capabilities, briefly described above, make them suitable sources of radiation for wide range of applications in both the fundamental and applied scientific investigations as well in an increasing number of advanced technologies [31-33]. The most widely known field, where the gyrotrons have demonstrated both their capabilities and potential for further progress is the fusion research. The gyrotrons are used for RF plasma production, electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD) and for diagnostic of magnetically confined plasma in various thermonuclear reactors (tokamaks, stellarators). Recently, the high performance gyrotrons for fusion have reached output power levels exceeding 1.0 MW in long pulse operation. For the next generation of fusion installations, such as ITER or DEMO, gyrotrons capable to produce 2 MW/CW and even higher power are being developed now.

Powerful gyrotrons are also used for production of multiple charged ions in ECR ion sources (ECRIS) for injectors into linear accelerators, Van-de-Graaff generators or cyclotrons in nuclear and elementary particle physics as well as for surface physics investigations.

Another application, which benefits immensely from the advancement of the gyrotrons towards high powers and frequencies, is the microwave processing of materials. Among the most important technologies are sintering (firing) of ceramics [34], modification of thin films, welding and coating [35]. Typical parameters of the so-called technological gyrotrons are frequency of 28 GHz and output power 10-30 kW, which produces a high heat flux (up to 15 kW/cm²) and
rapid heating (more than $10^5 \, ^\circ\text{C/s}$) at normal and low pressure. The microwave treatment by gyrotron radiation has many advantages over the conventional processing based on magnetron sources (2.45 GHz) due to the higher frequency and shorter wavelengths of the irradiating waves. The gyrotron beams are efficient tools for annealing of any dielectric material because of its capacity for volumetric uniform and controllable heating with high temperature ramp. The high quality of the process makes it especially suitable for treatment of semiconductor materials on heat-sensitive substrates, solar cells, glass etc [36]. Ultra-short annealing of silicon wafers allows eliminating the interdiffusion which is a problem when the chips are processed at high temperatures. To solve this challenging problem, CCR [37] is using high-power microwave radiation, produced by gyrotrons operating at 110 GHz, to rapidly heat the Si chips to 1300°C. CCR achieved ramp rates that exceed 250,000 C/s, allowing the chips to reach the target temperature of 1300 °C in only a few milliseconds. Because the skin-depth of the radiation is about 0.1% of the sample thickness, and because the ramp rates are so rapid, most of the sample remains cool throughout the heating process. The gyrotron radiation finds also application in ultra rapid curing, laminating and drying. The curing by gyrotron radiation is a “cold” process, which is characterized by a high degree of cross-linking that gives durability, high tensile and impact strength to the product.

Recently both the advantages and the disadvantages of the communications with THz carrier waves have been discussed in [38]. The obvious handicaps of communications at THz frequencies arise from the strong absorption through the atmosphere due to oxygen and water molecules. It is clear however that for satellite-to-satellite communication in space this problem does not exist. Curiously enough, in some cases the atmospheric attenuation could even be useful, e.g. for tactical military short-range transmission where this factor together with the straight line propagation of the signals allows covert communications since these signals simply will not propagate to distant listening posts. More importantly, however, the utilization of higher (sub-terahertz and terahertz) frequencies offer larger bandwidth and therefore higher transmission
rate compared to microwave communications, without having to switch to
different type of hardware such as lasers for optical communications. At the
same time, the size of the antenna will be reduced, which is advantageous for
the smaller satellite systems. THz waves can be used also for indoor wireless
communications. In this case, the advantage is that the THz carrier can provide
multiple data channels with gigabit per second or greater capacity.

Various factors affecting both the feasibility and the performance of the
communications and radar systems operating in the sub-terahertz region have
been studied in [39]. The upper limits of operational frequency are found to range
from 150 GHz to 700 GHz depending on the application.

Following the recent successful demonstration of a 10-Gbit/s wireless link
technology at 120 GHz [40] now plans for development of the electromagnetic
region from 300 GHz to 1 THz are under consideration.

A move into the millimeter wave region is beneficial for the radars since it
allows obtaining a high energy density and angular resolution in space with
realistic transmitter power and antenna aperture. Megawatt radar operating in a
Ka band was built using gyro-klystrons [41]. Since the radiation of the sub-
terahertz gyrotrons interacts strongly with atmospheric aerosols and trace
impurities, these sources have a great potential as atmospheric sensors and
promise to increase both the range and sensitivity by at least one order of
magnitude [42]. They are especially suitable for millimeter cloud radars at 94
GHz because such waves have the unique capability of scattering weakly from
cloud aerosol droplets, which really define the cloud, while at the same time
propagating easily through the cloud. As shown by Manheimer [42], the tunable
gyrotrons open up a new capability of absorption measurements over long
horizontal path lengths.

In recent years, the Electron Spin Resonance (ESR) spectrometers
utilizing gyrotrons as radiation sources have demonstrated their advantages in
the field of high-frequency spectroscopy for the study of the magnetic properties
of materials [43]. An advanced ESR spectrometer using the Gyrotron FU series
as millimeter and submillimeter wave source and a pulse magnet with a
maximum field intensity of up to 40 T has been developed. Important advantage of the spectrometers based on gyrotrons is the sufficient power, which makes possible single pulse measurements. The spectrometer has been used successfully for studies of the magnetic properties of various materials, notably for investigation of Fe-SiO$_2$ granular films, anomalous magnetization in CsFeCl$_3$, high-field spectra in powder samples of BaCu$_2$(PO$_4$)$_2$ and SrCu$_2$(PO$_4$)$_2$ compounds as well as in antiferromagnetic single crystal MnF$_2$.

The nuclear magnetic resonance (NMR) spectroscopy is a powerful analytical tool for study of the structure of the complex bio-molecules (e.g. proteins) but is characterised by poor sensitivity. There are two main possibilities to increase the signal to noise ratio. One is to use higher magnetic fields, which requires proportionately higher frequency of the microwave irradiation. The second one is to use a technique known as dynamic nuclear polarization (DNP) for enhancement of the signal. The gyrotrons are considered as promising radiation sources for the next generation of high field NMR-DNP spectroscopy because they are capable to deliver high power microwaves within an appropriate frequency range. The main challenge is to develop frequency tunable gyrotrons with high stability in the phase, frequency, and amplitude of the output signal during long periods at CW operation. Such unique gyrotrons are under development now at MIT [44] and FIR FU [45].

Another prospective application of the gyrotrons as powerful radiation source is in a novel spectroscopy which exploits the pump and probe technique and is called X-ray Detected Magnetic Resonance (XDMR). In this spectroscopy X-ray Magnetic Dichroism is used to probe the resonant precession of the magnetization pumped by a magnetic field that oscillates at microwave frequencies in a plane perpendicular to the static biased magnetic field. A distinguishing feature of the XDMR is that it is an element selective local probe and can be used for detailed study of the precession dynamics of orbital and spin magnetization components of different nature and origin. The estimates show that at sub-THz frequencies the required power of the pumping radiation is in excess of 1 kW. There is no other source except the gyrotron which could deliver
such power at frequencies around 300 GHz. The amplitude and frequency modulation of the gyrotron radiation is favorable feature for the XDMR experiments which not only facilitates the separation of the signal from the noise but at high modulation frequency will allow also to study the relevant relaxation phenomena. The most challenging requirement is to keep the stability of the output power within ±1 % in a CW regime during several days. Such unprecedented demand is not an easy task and its fulfillment certainly will require a careful optimization of the tube and appropriate stabilization system.

Biological applications are based on the specific spectroscopic fingerprints of living matter in the THz spectral regions. The different values of the absorption coefficient and index of refraction between water and tissue carbonated proteins at such frequencies, provide a unique contrast mechanism for biomedical imaging applications. This together with the specific absorption and reflection spectra will be used in novel diagnostic methods, for example early detection of cancerous cells, inspection of teeth and so on. Some promising application of the sub-millimeter wave microwave therapy (e.g. RF hyperthermia) to new medical technologies are in progress worldwide. Unlike other techniques based on the use of ionizing radiation (X-rays, radionuclides) the terahertz imaging and spectroscopy does not damage the DNA and is considered as absolutely harmless.

We are also well aware of many military applications of strong microwaves generated by gyrotrons (e.g. directed energy weapons, non-lethal weapons (aka crowd dispersing, active denial systems etc.), detection of concealed weapons and explosives as well as screening of products but will not discuss them here due to the limited volume of this short review.

5. Conclusions

The gyrotrons are the most powerful radiation sources in the sub-terahertz region of the electromagnetic spectrum. Recently they have passed the breakthrough threshold of 1 THz demonstrating their capacity for further advancement toward higher frequencies in the terahertz spectral range. In the
years to come, the progress in this direction will depend on the availability of more powerful superconducting magnets at reasonable/affordable prices. In the meantime, the gyrotrons based on pulsed and hybrid solenoids are considered as an adequate alternative. Other promising prospect for the terahertz gyrotrons relies on the development of large-orbit gyrotrons (LOG) operating at higher harmonics and using 10-20 T magnets. The LOG concept is beneficial also for the sub-terahertz range, where high harmonic devices can be built using permanent magnets. A common tendency for all gyrotrons will be further improvement of their performance (enhanced efficiency, stability of the output parameters during long periods of operation, broader tunability, easier maintenance due to the utilization of cryogen free magnets etc.) together with a corresponding sophistication of the means and subsystems for diagnostic, control and transmission of the radiation towards the target, where it will be used. Such progress will be made possible through the development of adequate physical models and computer codes for numerical simulation, computer-aided design (CAD) and optimization of the next generation of gyrotrons.

Alongside with the classical areas such as the fusion research and the microwave materials processing where the gyrotrons are traditionally used as powerful radiation sources several novel fields of application are emerging for which the most important is their capability to deliver coherent radiation at higher frequencies. Among them are several spectroscopic techniques, namely ESR, DNP/NMR and XDMR. An increasing utilization of terahertz radiation produced by gyrotrons is anticipated in various new methods for investigation of matter in atomic physics (e.g. level excitation in positronium). The gyrotrons have also potential to be used for terahertz imaging, screening, in radars and in the telecommunications. Probably the future will witness also more intensive use of the gyrotrons in novel medical technologies (e.g. tumor detection and ablation), microwave-enhanced chemistry, microwave-assisted organic synthesis and others. As with any new technology it is difficult to predict the most important application. It is quite possible that novel uses not mentioned in this short review will emerge in the future. In any case however they will be born by the potential
which the gyrotron has for bridging the terahertz gap. The aim of the authors of this paper was just to give an idea about the current status and the expected uses of the powerful gyrotron radiation anticipating that some of their readers may well be among the people who will contribute to the broadening and refinement of existing application or invent novel ones.

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