OVERVIEW OF TERAHERTZ RADIATION SOURCES

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Abstract

Although terahertz (THz) radiation was first observed about hundred years ago, the corresponding portion of the electromagnetic spectrum has been for long time considered a rather poorly explored region at the boundary between the microwaves and the infrared. This situation has changed during the past ten years with the rapid development of coherent THz sources, such as solid state oscillators, quantum cascade lasers, optically pumped solid state devices and novel free electron devices, which have in turn stimulated a wide variety of applications from material science to telecommunications, from biology to biomedicine. For a comprehensive review of THz technology the reader is addressed to a recent paper by P. Siegel [1]. In this paper we focus on the development and perspectives of THz radiation sources.

INTRODUCTION

Throughout this paper we will use a definition of the THz region that extends over two decades in frequency, covering the spectral range from 100 GHz to 10 THz. This should allow a better understanding of the effort in the extension of microwave electronics towards high frequencies on one side and the development of photonic devices from the optical region towards low frequencies. According to this scheme, we will first cover the state of the art of solid state oscillators and then move to gas and Quantum Cascade Lasers (QCL), which lie at the low and high frequency boundary of the THz region respectively. A brief review of laser driven THz emitters will be presented, which are the most widely used sources of THz radiation. We will also briefly discuss the physical principles of the generation of THz radiation from free electrons, describing the mechanism of Coherent Spontaneous Emission and the development of table-top Free Electron Laser (FEL) sources.

SOLID STATE OSCILLATORS

Electronic solid state sources, like oscillators and amplifiers, are generally limited in frequency due to the transit time of carriers through semiconductor junctions, which causes high frequency roll-off. High frequency Gunn, IMPATT and TUNNET diodes are being developed by several research groups [2]. They are rugged and compact devices and can operate CW at room temperature with a relatively narrow linewidth (10^{-6}). A CW power of about 100 mW can be obtained around 100 GHz. The output power falls off as $1/f^2$ and then as $1/f^3$ as the frequency increases (see Fig. 1). Frequency multipliers with two or more diodes are generally employed to reach frequencies above 200 GHz, up to about 1 THz. The average power level achievable in the region around 400 GHz is typically in the range 0.1 to 1 mW. Due to their compactness, the range of application of these sources is rapidly growing. A 200 GHz Gunn diode is being used as a source in a low cost imaging system under development at RPI-Troy for security applications [3].

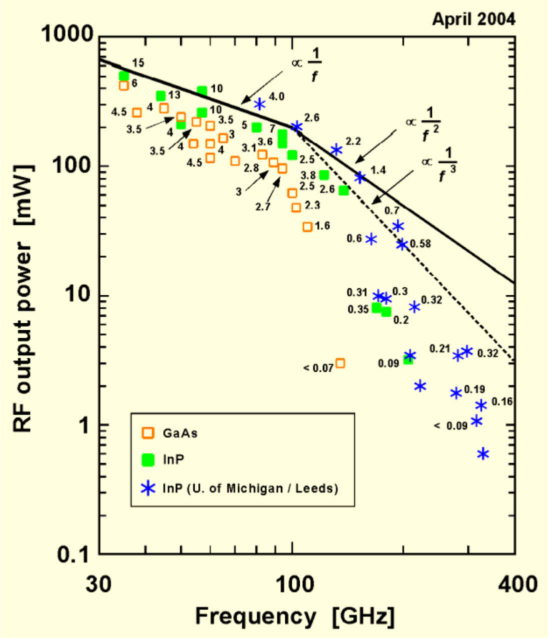

Fig. 1: State of the art results from GaAs and InP Gunn devices. Numbers next to the symbols denote dc to RF conversion efficiencies in percent (courtesy of H. Eisele, University of Leeds, UK).

GAS AND QUANTUM CASCADE LASERS

The Far Infrared (FIR) gas laser and the quantum cascade laser (QCL) are respectively the oldest and the newest coherent source developed in the THz region. Gas lasers date back to the sixties [4]. They are optically pumped lasers, which use a CO_2 laser to excite the roto-vibrational levels of gas molecules at pressures in the mbar range. The most widely used gas is methanol, which provides a powerful (typically 100 mW) emission line at 118 μm. Gas lasers are line-tunable in the range 0.3 to 5 THz (1000 to 60 μm) although with limited power and are commercially available by several companies, among which Coherent Inc. and Edinburgh Inst. The technology of FIR lasers has seen modest development in recent years, as it has been the case of most gas lasers. However they still are ideal sources for specific applications in which continuous tunability is not a must, like for instance heterodyne spectroscopy and plasma diagnostics.

QCLs, the most recently invented optical lasers [5], have seen an impressive development in the THz region during the past two years. In a Quantum Cascade Laser, electrons are injected into the periodic structure of a superlattice under electrical bias. They undergo intersubband transitions with THz photon emission excited by resonant tunneling through the multiple wells. As a result a cascade process occurs, which gives name to the source.

The first QCL to operate in the THz region was developed by a joint collaboration between NEST-Pisa and the Cavendish Laboratory, Cambridge. It emitted at 4.4 THz providing about 2 mW of average power with 10% duty cycle at an operating temperature of 50 K [6]. Starting from this result, a great effort has been undertaken by several research groups worldwide (NEST-Pisa, Cavendish-Cambridge, MIT, Sandia, Neuchatel University), which has led to the record operating temperature of 137 K pulsed and 93 K CW achieved at MIT [7]. The group at MIT also holds the record of the longest wavelength (~141 μm, 2.1 THz) QCL to date without using magnetic fields [8], while the group at Neuchatel has recently reported an average output power approaching 50 mW [9]. 2.5 THz low threshold CW operation has been obtained at NEST-Pisa [9]. Recent progress in the QCL field also includes the development of THz QCLs using metal-semiconductor-metal waveguides for mode confinement. This method will be advantageous or even crucial as longer wavelengths are approached.

Among the solid state lasers, we also recall the p-type Ge laser [10], which can be tuned between 1 and 4 THz, but requires low temperature operation (20 K) and a large (1 T) applied magnetic field.

LASER DRIVEN THz EMITTERS

Today's most widely used sources of pulsed THz radiation are laser driven THz emitters based on frequency down-conversion from the optical region. Two main techniques have been developed to produce THz radiation. The first one is based on a short pulse (femtosecond) Ti:Sapphire laser [11, 12], which illuminates the gap between closely spaced electrodes on a photoconductor (e.g., silicon-on-sapphire or GaAs) generating carriers, which are then accelerated by an applied bias field (100 V). The resulting current transient, which is generally coupled to an RF antenna through a stripline, radiates in a wide band at THz frequencies corresponding to the Fourier transform of the laser pulse time profile. The upper limit in frequency for these devices is given by the carrier recombination time in the semiconductor and by the bandwidth of the stripline.

A similar terahertz spectrum can be obtained by applying a sub-picosecond laser pulse to a crystal with a large second-order susceptibility like ZnTe [13]. Due to the nonlinear response of the crystal, photomixing occurs, producing a time-varying polarization which in turn gives rise to THz emission. In this case higher frequencies can be reached due to the fast response of the crystal and to the absence of any stripline or conductor. Both techniques and the related electro-optical detection are at the basis of most THz imaging systems [13, 14].

Laser driven solid state emitters also include CW photomixers, in which offset-frequency locked CW lasers are focused onto a photoconductor under bias. The laser induced photocurrent is modulated at the laser difference frequency and is coupled to an antenna, which emits THz radiation [15]. In this case a narrow band continuous wave emission is obtained, which can be tuned over a fairly wide range by shifting the optical frequency of one of the two drive lasers.

The typical frequency range covered by laser driven solid state emitters is 0.2 to 2 THz or higher depending on the laser pulse parameters. Average power levels range from nanowatts to hundred microwatts and pulse energies are typically in the femtojoule to nanojoule range.

FREE ELECTRON BASED SOURCES

Free electron based sources like Klystrons, Travelling Wave Tubes (TWT), Backward Wave Oscillators (BWO) and Gyrotrons have been extensively studied since the mid of the past century to approach the high frequency part of the microwave region. With the exception of Gyrotrons, which are generally designed to reach high average power and deserve a review on their own [16], the above free electron sources suffer from simple physical scaling problems, metallic wall losses and the need for high magnetic and electric fields, as well as high electron current densities as the frequency is increased. For this reason, TWTs have received little attention as candidate sources of radiation above 100 GHz.

The BWO [17] is a slow wave device where the electrons spiralize through a corrugated structure in an axial magnetic field interacting with the first spatial harmonic of the backward wave. Indeed, in this region of the dispersion relation, the phase velocity of the wave is positive and the group velocity is negative. BWOs are table top devices that can operate in the THz region at moderate power levels (1 – 100 mW). The technology of BWOs has been mostly developed in Russia and they are now commercially available through companies in the US and Europe. BWOs operate with an accelerating potential in the range 1 to 10 kV and axial magnetic field of about 1 T. They can be tuned over tens of GHz by varying the accelerating potential. A number of different BWOs can be implemented in an integrated system to cover altogether a wide frequency range extending from 30 GHz to 1.2 THz (see Fig. 2).

To overcome the necessity of reducing the physical size of the source components as the frequency is increased, different schemes have been developed to let the electrons exchange momentum and allow photon emission. The most frequently used one is the magnetic undulator originally proposed by Motz [18], which was employed by Phillips in the Ubitron [19] back in 1960 to generate mm-wave radiation and which led to the realization of the

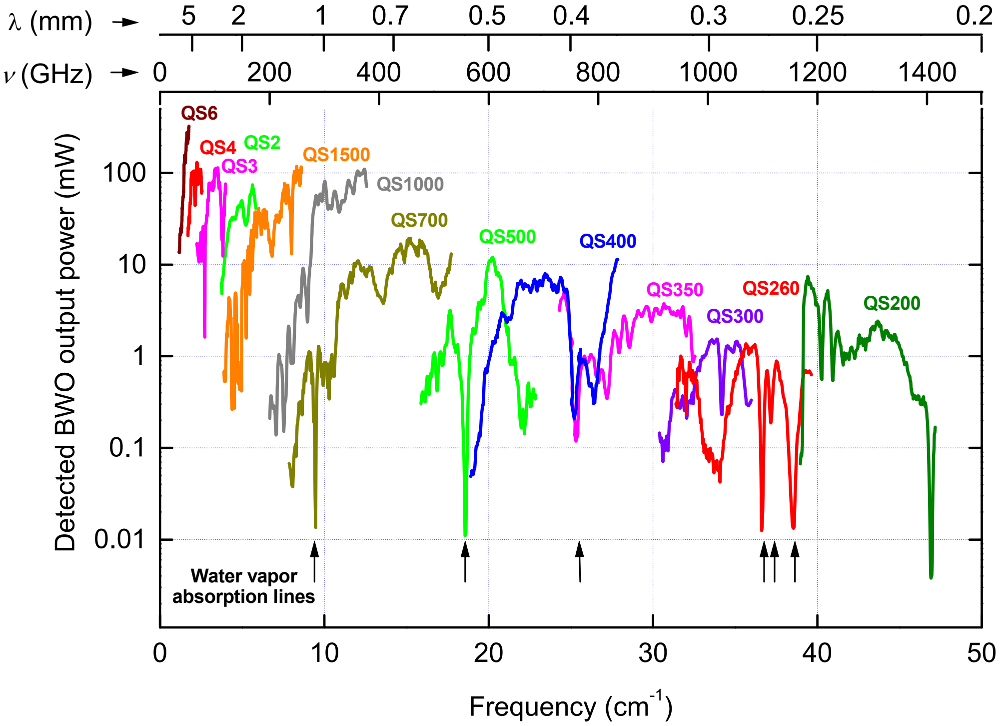

Fig. 2: Output power and spectral distribution of BWO devices employed in a CW spectroscopic system at the 1st Physics Institute of the University of Stuttgart. (Courtesy of M. Dressel, University of Stuttgart)

first Free Electron Laser (FEL) in 1977 [20]. Other free electron devices are the Cerenkov FEL, based on the interaction with a dielectric loaded waveguide [21], and the Metal Grating FEL, based on the Smith-Purcell effect [22].

Coherent spontaneous emission

In his pioneering work on the undulator radiation [18], Motz pointed out that in a uniform electron beam the contributions of individual electrons to the radiation field are random in phase, and therefore the square of the total field equals the sum of the squares of the individual fields. If the electrons were bunched within a distance comparable to the wavelength of the radiation, their fields would add up in phase, resulting in the emission of coherent radiation with a power level several orders of magnitude higher than the non-coherent radiation generated by a uniform beam. The idea of generating coherent radiation in the THz region utilizing bunched electron beams, such as those produced by radio-frequency (RF) accelerators, was indicated in [18], and different coupling structures, designed to extract energy at a harmonic of the bunch repetition rate, were investigated [23]. More recently the coherent spontaneous emission from an RF-modulated electron beam at wavelengths comparable to the electron bunch length has been the object of renewed interest because of its relevance in the generation of short pulses of coherent THz radiation [24, 25, 26]. Issues like the dependence of the emitted radiation on the bunch shape [27] and the observation of emission at discrete frequencies, which are harmonics of the fundamental RF [28], have also been addressed both theoretically and experimentally and have led to the realization of compact FELs in the THz region [29, 30].

FEL Facilities and THz Synchrotron Sources

Historically, the first Free Electron Laser facility to provide THz radiation to users has been the UCSB-FEL, which is driven by an electrostatic accelerator and operates in a quasi-CW mode. It provides tunable terahertz radiation in the region from 120 GHz to 4.8 THz (2.5 mm - 60 μm) with an output power in the range from 500 W to 5 kW and a pulse duration of 1 – 20 μs at 1 Hz repetition rate [31]. Several facilities have been built to operate in the infrared region and most of them can reach or plan to extend into the THz region. Besides the UCSB FEL, we recall here the Israeli EAFEL (100 GHz), based on a 6MeV EN-Tandem Van der Graaff accelerator [32], the Stanford FEL (15 – 80 μm) [33], FELIX (3 – 250 μm) with its planned FELICE extension for intracavity experiments at FOM-Nieuwegein [34], CLIO at LURE-Orsay, which has plans for a new hybrid resonator to reach wavelengths in the range 100 – 300μm [35], ELBE, which has recently lased at 20 μm and has plans to extend its operation to 150 μm [36], and the THz-FEL at Novosibirsk, based on a CW energy recirculated linac

(ERL) and providing about 100 W in the spectral range 120 – 180 μm [37].

The principle of coherent spontaneous emission is also exploited to generate THz radiation from bending magnets at FEL facilities and Synchrotron facilities. About 100 W of CW radiation have been produced from bending magnets in the band from 0.1 to 3 THz at JLAB [38]. The JLAB ERL accelerator overcomes some of the limitations of conventional linacs and storage rings. It produces 500 fs, 135 pC electron bunches at a very high repetition rate (75 MHz) by using superconducting RF cavities and recovering the energy of the spent electron beam. Coherent THz emission from a linac driven beam has been demonstrated at Brookhaven National Lab (see below). Coherent synchrotron radiation has also been observed in storage rings [39, 40, 41, 42]. A coherent THz beam line is operating at BESSY-Berlin and several others are planned at Lawrence Berkeley National Lab (CIRCE), Cornell University, and Daresbury (4GLS).

Compact FELs and Table Top Free Electron radiators

There also exist accelerator-based THz sources, which can fit on or scale to the size of a table-top. They are proof-of-principle experiments and should be looked upon as ideas that can be specified and tailored for particular types of experiments. Development work on electron beam based sources is under way at several sites. The RF-gun derived sources described below will benefit from ongoing design work, especially if electron guns can be made superconducting. Laser wake-field accelerators are actively being researched as possible alternative solutions for high energy systems and are still in the early stages of development. Some of these sources could be designed to produce half-cycle pulses of THz radiation.

In a table-top free electron radiator based on an RF modulated electron beam with short bunches, the modulator, klystron, waveguide, cooling, magnets, electron gun, accelerating structure, and all other peripheral accelerator components could easily be fitted into the space of 3 cubic meters. The FEL-CATS source at ENEA-Frascati [43] and the source under development at ANL [44] are examples of this compactness. Further engineering work and improved design in the X-ray shielding of the accelerator will also increase the compactness of these systems.

The coherent prototype radiator at Argonne National Laboratory (ANL) employs three different cathode types – thermoionic, photo-gated thermoionic, or photocathode. Even at a low RF repetition rate, as well as normal conducting, relatively high average powers are achievable if a laser gates the thermoionic cathode. The electron beam pulse length changes depending upon the cathode mode of operation and the degree of compression. Although this source is a prototype, it can be easily adapted to a specific experiment and packaged into a small space. The repetition rate, pulse width, average and peak power can be improved significantly.

At ENEA-Frascati the recently built source FEL-CATS utilizes a high-efficiency generation scheme based on the mechanism of coherent spontaneous emission, which allows operation in the frequency range between 70 GHz and 0.7 THz. Tunable operation has been obtained in the spectral region between 0.4 and 0.7 THz with a relative linewidth of about 10% FWHM [45]. The radiation has a pulsed structure composed of wave-packets in the 3 to 10 ps range, spaced at a repetition frequency of 3 GHz. A 5 microsecond long train of such pulses (macropulse) is generated and repeated at a rate of few Hz. The measured power in the macropulse is 1.5 kW at 0.4 THz.

The principle of operation of the source is based on the coherent spontaneous emission from short bunches of relativistic electrons. The FEL source utilizes a 2.5 MeV RF linac to generate the electron beam, which is injected into a linearly polarized magnetic undulator composed of 16 periods, each 2.5 cm long with a peak magnetic field of 6000 Gauss. A second RF structure, called Phase Matching Device (PMD), is inserted between the linac and the undulator and is controlled in phase and amplitude to correlate the electron distribution in energy as a function of time in the bunch [46]. In this way the contributions to the total radiated field by individual electrons in the bunch are added in phase, leading to a manifold enhancement of the coherent emission.

In the frame of a collaboration between University of Maryland and the Brookhaven National Laboratory (Source Development Laboratory) a proof of principle experiment based on the modulation induced on an electron bunch has been recently carried out [47]. This device uses a laser to generate a bunch train of electrons through photoemission. Each bunch is about a picosecond long, and they are separated by about a picosecond. An electron accelerator takes these short bunches and accelerates them up to 70 – 72 MeV. At this point the beam is intercepted by a mirror. When the environment around the beam changes from vacuum to metal, transition radiation is emitted. Because of the way the electrons are bunched, there is strong emission in the terahertz frequency range. The frequency spectrum can be controlled by controlling the way the electrons are initially bunched. The result is a tunable terahertz source that could be used for a wide variety of additional experiments.

At the Source Development Laboratory, Brookhaven National Laboratory, a linac-based source of coherent THz pulses has been developed. In this device electron bunches are compressed to ~300 fs rms. The degree of compression can be varied with the perspective of reaching 100 fs and possibly shorter pulse duration. Electron bunches produce single-cycle coherent THz as transition radiation or dipole radiation. An energy per pulse of ~100 μJ and peak electric field up to > 1 MV/cm has been demonstrated [48]. The method could be improved to produce shorter electron bunches and a broader spectral range. A pulsed laser driving the linac photocathode provides synchronized IR pulses for electro-optic coherent detection of THz pulses.

Advanced Energy Systems (AES) has plans to develop a multi-watt (50 – 100 W eventual goal; 5 W in this initial prototype), tunable, compact THz source.

Intense THz radiation from ultra-short electron bunches has been generated by a laser wakefield-based linac at Lawrence Berkeley Laboratory. This source is based on the production of ultra-short (< 50 fs rms), high charge (0.3 – 5 nC) relativistic electron bunches by using a laser excited plasma wave with large enough amplitude to trap background electrons and accelerate them in mm distance to 10's of MeV. As the electrons exit the plasma, a burst of transition radiation is produced. The source performance is controlled by the electron bunch properties and the density and transverse size of the plasma at the exit boundary. The THz radiation is intrinsically synchronized with an external laser and experiments are underway to measure the THz pulse structure with electro-optic sampling. Time averaged spectra have been measured and show that the spectrum with the present configuration is centered around 2 THz. Whereas presently energy levels on the order of 0.1 μJ/pulse have been collected, modeling indicates that significantly higher power can be achieved by optimizing the plasma properties (transverse size and longitudinal profile) and could be as high as 100 μJ/pulse [49]. Further progress on the laser driven accelerator performance is underway, including the production of quasi-monochromatic (few % energy spread) relativistic electron bunches (100 MeV), which will lead to intense radiation emission from conventional transition radiation foils.

MICROFABRICATED SOURCES

A challenge for the future is the further reduction in size of compact FELs. A Smith-Purcell emitter using a CW electron microscope gun as electron source has been developed at Vermont Photonics [50], providing CW power levels up to 10 microwatts at wavelengths in the range from 200 to 900 μm with an output bandwidth of about 1 to 2 cm^{-1}. This source is devoted to research applications like THz absorption spectroscopy, THz pump/probe experiments in biology and nanotechnology, test of bolometric arrays for THz astronomy, test of THz imaging concepts. New developments are in progress with corporate partners to provide output power in the mW range and to extend the tuning range from 100 to 1500 μm. Experiments and proposals are also in progress at Chicago University [51] and Vanderbilt University, where a 45 – 65 kV gun equipped with a laser driven needle cathode is being assembled to drive a miniaturized Smith-Purcell emitter with a 200 μm period grating [52]. The device is designed to operate in the range 0.3 – 0.7 THz.

The possibility of using "Computer Controlled 3-D Electron-beam Induced Deposition and Etching" to realize microfabricated Smith-Purcell emitters has been investigated at NawoTech (Germany) [53].

CalCreek Research (CCR) is developing miniaturized, efficient traveling wave tube (TWT) amplifiers incorporating micro-electro-mechanical systems (MEMS) fabrication techniques [54]. The MEMS based TWT is designed to provide 10 W of RF power at 83.5 GHz with 5 GHz bandwidth for communication applications in micro-satellites.

CONCLUSIONS

The development of a variety of THz sources has been gradually filling the THz gap in recent years, providing complementary characteristics in terms of frequency of operation, average and peak power.

Large scale FEL facilities are capable of providing high power CW THz radiation while low-cost solid state oscillators and QCLs are expected to drive the realization of THz systems for a variety of applications in the near future.

It has been shown that low-cost small size FELs can also be built in the THz region. Their peculiar feature is the capability of providing high peak power in the kW range with peak electric field in the range 10^4 – 10^6 V/cm, which is crucial for the investigation of non-linear phenomena. The generation of ultra-short electron pulses (50 – 100 fs) will significantly increase the available bandwidth of free electron THz radiators, and improvements in RF-gun technology will make a table-top high power CW source a possibility in the near future.

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