Monitoring Terahertz Technology

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Summary

In this first report we give an introduction to the basic concepts of terahertz radiation, as well as an overview on several approaches and materials used to generate and detect terahertz radiation like: electronic, solid state, continuous wave and pulsed. The most relevant methods for generation, detection and modulation of terahertz for the application in the communication area are described. Relevant aspects to the use of terahertz radiation in this field are outlined indicating advantages and disadvantages. Atmospheric attenuation in the terahertz frequency range is discussed. Advantages of terahertz systems over infrared or quantum cascade laser radiation are presented. A projection of terahertz in the communication area is proposed indicating a potential in both short and long range applications, for the near and far future, and the most promising terahertz systems for a practical terahertz system are identified.

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The aim of this terahertz technology monitoring study is to bring an insight on different aspects of this novel technology and its potential application in the communication area. The main topics to be covered in this 12 months period are:

- Present and future concepts for generation detection, modulation, transmission and propagation.
- Possible frequencies for transmission channels (or transmission lines).
- Materials for transmission channels: attenuation and reflection parameters
- Attainable Bandwidths
- Achievable transmission distances: in air and dependences on atmospheric parameters.
- Used frequencies and interferences.
- Aspects of military use.
- Projection and what is to be expected for the next 6 to 12 years.
- Most important aspects.

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Introduction

In the last 10 years, the field of terahertz (THz) technology has gained an enormous attention in the different fields of applications such as: spectroscopy [1-2], biomedical imaging [3], DNA analysis [4], product and packaging control [5], security applications [6] and communication technology. This technology has been known to scientist since more than 30 years, and its remarkable increase initiated by the fantastic laser development in the last 10 years has lead to the development of various powerful sources of THz radiation. These sources have made possible experimental demonstration in laboratories and further improvements are showing the potential of this technology.

In the electromagnetic spectrum (illustrated in Fig. 1) the “Terahertz Gap” goes from 200 GHz (0.8 Mev) to 10 THz (40 MeV).

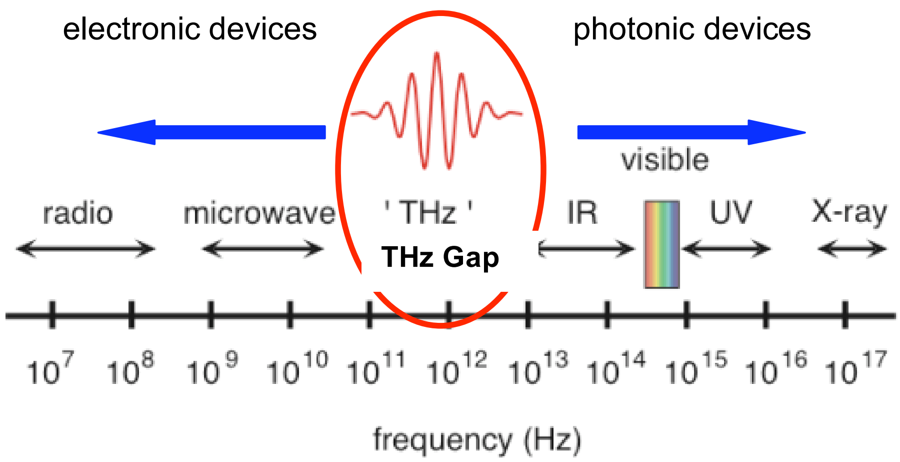

Figure. 1. The terahertz Gap in the electromagnetic spectrum.

Within this “Gap” frequencies are too high for conventional electronics and photon energies are too small for classical optics. If this gap is approached from the high-energy (infrared) side, the problem is the design of optical systems with dimensions close to those of the wavelengths concerned. If the region is approached from the low-energy (millimeter wave) side, there is also the difficulty of realizing appropriate circuits to handle signals at this high frequency.

Although difficult, there are many important reasons why the terahertz range is of intrinsic scientific interest and rich in potential applications:

- THz radiation is non-ionizing
- penetrates visually opaque materials,
- experiences less Rayleigh scattering than infrared radiation
- interacts strongly with water, but goes through 1 mm of biological tissue
- goes through 1 km of fog
- is reflected in metal.

In addition many material excitations lie in the THz range thus providing chemical "fingerprints".

In the following sections we will first give an overview on methods for generation and detection of terahertz radiation. Aspects on modulation, transmission and propagation, frequencies and materials for transmission channels will also be included. Some aspects of terahertz in the communication area will be also introduced.

1. Generation of THz

Terahertz radiation is easily accessible by means of blackbody radiation, but it is a challenge to separate the signals from the natural background.
Terahertz sources can be broadly classified as:

- Incoherent thermal sources: broadband pulsed sources (Optical Generation)
- Narrow band continuous-wave sources (Electronics and Quantum Cascade Lasers)

We will give an overview of these techniques and provide details in some examples that are relevant to the purpose of this monitoring.

1.1 Broadband THz sources

Most broadband pulsed THz sources are based on the excitation of different materials with ultrashort laser pulses. Photoconduction and optical rectification are two of the most common approaches for generating broadband pulsed THz beams. Optical methods are used for the generation of broadband terahertz sources, and due to the increasing progress in laser technology these methods have been the most developed in the last 20 years. We can mention two representative methods: **Photoconduction and Optical Rectification**. Both methods used pulsed femtosecond lasers.

In the **photoconductive** approach a femtosecond laser generates an ultrafast photocurrent in a photoconductive switch or semiconductor using electric-field carrier acceleration [12]. Figure 2 shows a simplified scheme of a photonductive antenna also known as Auston switch, showing the three main elements of such a device: 1) the dipole antenna, 2) the photoconductive materials which lies in the gap between the antenna and 3) the contact pads with the connection to the dipoles/photoconductor. Typical dimensions for the length of the dipole are between a few tens of µm up to several hundred of µm. The gap with the photoconductor is a few µm wide. The length of the whole device is about 1-2 mm.

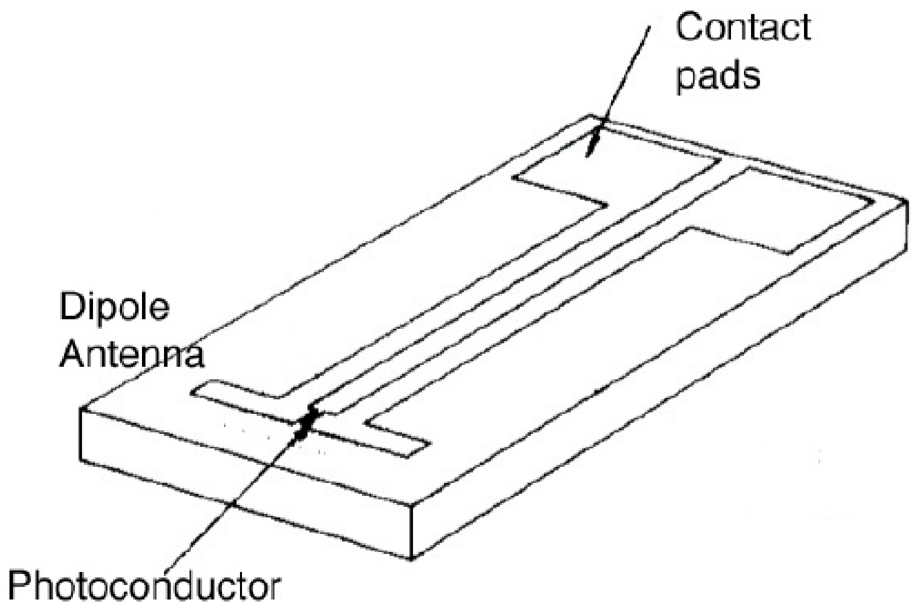

Figure. 2. Antenna structure consisting of the “Hertian Dipole”, photoconductor and contact pads. Contact pads, coplanar stripline and antenna are made out of silicon.

For the operation of the device a dc voltage is applied to the contact pads and consequently to the photoconductor. A fast optical laser pulse (100 femtoseconds) is focused onto the photoconductor so that only part of the photoonductor is illuminated. The wavelength is sufficient to excite charges over the bandgap in the photoconductor. Because of the applied electric field applied to the contact pads the excited charges are accelerated and subsequently decay with a time constant determined by the free-carrier lifetime in the phoconductive material. This leads to a pulsed photocurrent in the photoconductive antenna and to the terahertz radiation. The best material for the photoconductor has to have a short charge recombination lifetime, high resistivity (when there is no light) and a high carrier mobility.

Optical Rectification is an alternative mechanism for pulsed THz generation, A femtosecond laser is used as well but the energy of the terahertz radiation comes from the exciting laser pulse. In this case the conversion efficiency depends mainly on the nonlinear coefficient of the material. Other methods are difference frequency generation (DFG) or optical parametric oscillation (OPO), The nonlinear media receiving most attention are GaAs, GaSe, GaP, ZnTe, CdTe, DAST and $LiNbO_3$.
In optical rectification, a high-intensity ultrashort laser pulse passes through a transparent crystal material that emits a terahertz pulse without any applied voltages. Figure 3 shows a schematic of optical rectification with a pulsed femtosecond laser. It is a nonlinear-optical process, where a nonlinear material is quickly electrically polarized at high optical intensities. This changing electrical polarization emits terahertz radiation. It is called rectification because the rapid oscillations of the electric field of the laser pulse are “rectified” and only the envelope of the oscillations remains. Since the medium is non absorbing, the polarization instantaneously follows the pulse envelope implying that there is practically no limit on the speed at which the polarization can be switched on and off.

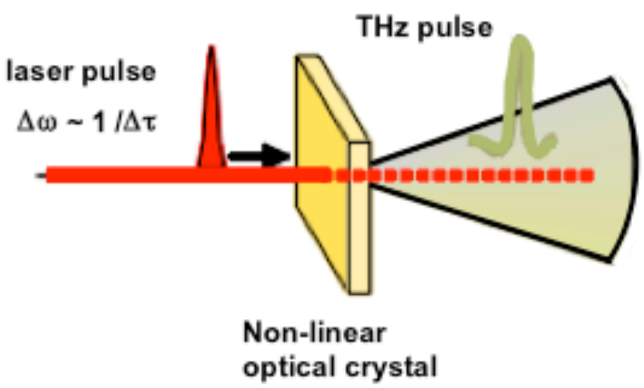

Figure 3. Optical rectification in a nonlinear optical crystal.

Because of the high laser intensities that are necessary, this technique is mostly used with amplified Ti:sapphire lasers and with the recently developed compact femtosecond pulsed lasers at 1.5 nm. Typical crystalline materials used in this configuration are zinc telluride, gallium phosphide, gallium selenide and DAST that with extremely high nonlinear optical coefficients is an ideal material for this configuration.
The bandwidth of pulses generated by optical rectification is limited by the laser pulse duration, terahertz absorption in the crystal material, the thickness of the crystal, and a mismatch between the propagation speed of the laser pulse and the terahertz pulse inside the crystal. Typically, a thicker crystal will generate higher intensities, but lower THz frequencies. With this technique bandwidths as large as 30 THz have been obtained using this mechanism [13]. It is possible to boost the generated frequencies to 40 THz or higher, although 2 THz is more commonly used since it requires less complex optical setups. One big advantage of this approach is the possibility of compact engineering with the progressing development of compact pulsed telecom lasers and new materials optimized for terahertz applications like DAST.

1.2 Narrow band THz sources

These type of sources are crucial for high-resolution spectroscopy applications as well as potential applications in telecommunications. Due to these reasons the research interest has been significant in the development of these sources. There are many techniques being currently in development including up-conversion of electronic radio-frequency sources (i.e. voltage-controlled oscillators and dielectric resonator oscillators), down conversion of optical sources, lasers and backwardwave tubes. These devices are well established at low frequencies. The most used technique for generating low power (<100 μW) continuous wave THz radiation is through up-conversion of lower frequency microwave oscillators [14] which uses a chain of planar GaAs Schottky-diode multipliers.

Extremely high-power THz emission has been demonstrated with **free-electron lasers** with energy recovering accelerators [15]. Free-electron lasers use a beam of high velocity bunches of electrons propagating in vacuum through a strong, spatially varying magnetic field. The magnetic field causes the electron bunches to oscillate and emit photons.

Another method initiated in 1970 uses **non-linear photomixing** of two continuous wave laser sources with slightly different frequencies combined in a material with high nonlinearity. This is the most common concept for the generation of cw THz radiation with diode laser sources. The basic idea is shown in Fig. 4. Two electromagnetic waves oscillating with frequencies f_1 and f_2 are coming either from two independent laser sources or from lasers operating at two frequencies simultaneously. Both waves are superimposed and generate an optical beat signal. This light field with the beat signal is focused onto a photomixer which is typically a semiconductor with an antenna structure deposited on it. The absorption of carriers in the photomixer is proportional to the square of the electromagnetic field E^2(t).

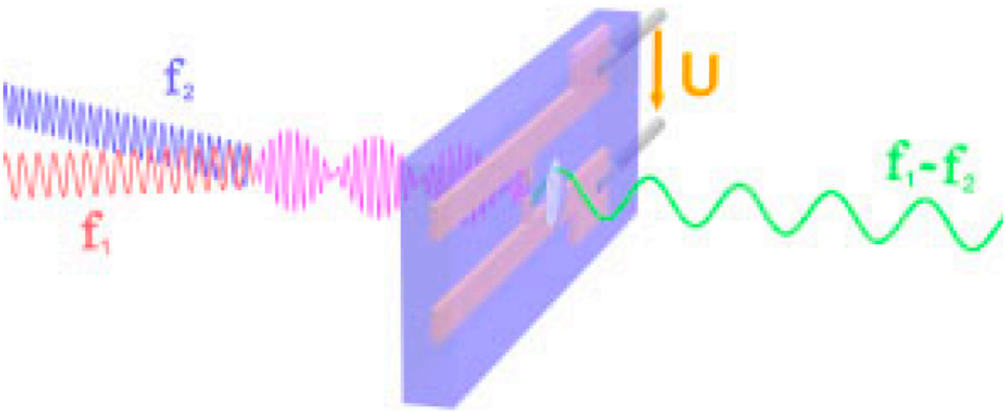

Figure 4. Generation of THz radiation in a photomixer with applied voltage U by down conversion of the two optical frequencies f_1 and f_2 to $f_1 - f_2$.

This electromagnetic field consists of a fast oscillation with the frequency $(f_1 + f_2)/2$ which is modulated with an envelope function modulated with the difference frequency $\nu_{21} = f_1 - f_2$. The generated carriers in the semiconductor cannot follow the fast oscillation at $(f_1 + f_2)/2$, so that the generation rate of the carriers is proportional to the difference frequency ν_{21}. When a semiconductor with a low carrier lifetime is chosen for the photomixer, the carrier density in the photomixer exited by the beat signal also oscillates with the difference frequency. The photomixer is biased with an external DC field, generated by te applied voltage U as shown in Fig. 4. In this way the photogenerated carriers in the photomixer are accelerated and give rise to a current I(t) modulated with the difference frequency ν_{21}. This current feeds then the antenna structure deposited on the photomixer and thus gives rise to an emitted THz wave oscillating with the difference frequency of the two driving optical modes. More details can be found in reference [16]. Typical output powers for photomixers are in the 1-2µW range for photoconducting antenna structures based on low temperature grown (LTG) GaAs. The operating wavelength is approximately 800 nm. The Fraunhofer Institute- Heinrich-Hertz-Institut in Germany (http://www.hhi.fraunhofer.de) has done extensive research in this area, Fig. 5 shows a fiber coupled THz emitter based on InP technology. This photoconductive antenna converts optical signals in the 1.5 µm wavelength range into THz radiation and viceversa. This novel InP based THz emitter and receiver chips are packaged into pigtailed modules (see Fig. 5) which can be used for handheld THz sensor systems replacing state of the art free space 800 nm systems on heavy optical benches.

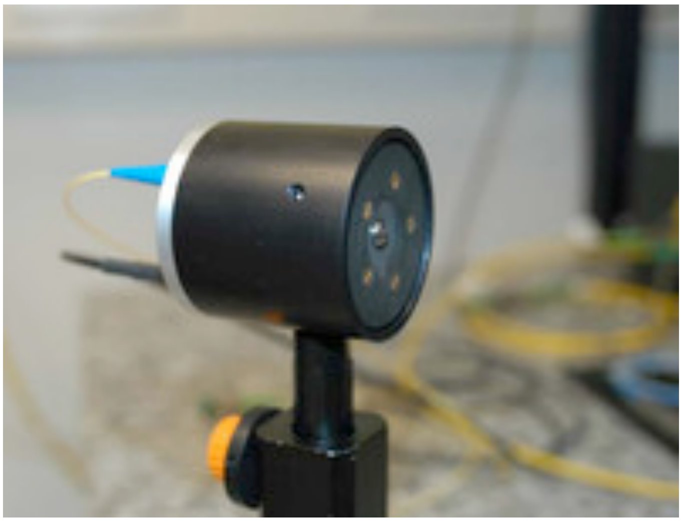

Figure 5 Fiber coupled THz emitter/detector head

Higher output powers of up to 11 µW can be achieved with more sophisticated concepts like the so called UTC-PD (unique traveling carrier photodiodes) based on InP/InGaAs pin photodiodes operating at 1.55 µm. In spite of the higher potential of photomixing components in the 1.55 µm wavelength range, the most common photomixers are still based on LTG-GaAs.

Initially low conversion efficiencies lead to low terahertz emission, but with better materials with higher second-order nonlinearities like DAST this method has to be considered for narrow band applications.

The improvement in nanotechnology has led to the development of semiconductor-based narrowband THz sources known as **quantum cascade lasers** (QCL). The first QCL was developed in 1994 [17] with a lasing frequency of 70 THz, and after several years of research in 2002 a quantum cascade laser with a frequency of 4.4 THz was demonstrated [18]. Contrary to conventional laser diodes where the optical transition takes place across the band gap through electron-hole recombination, QCL are semiconductor lasers in which only electrons are involved and the transition occurs within the subbands formed from the conductions band of a specially engineered heretostructure. Conventional laser diodes are bipolar interband devices while QCL are known as unipolar (only electrons) intraband (or inter-subband) emitters. Figure. 6 illustrates the working mechanism in a QCL.

An intense material research in nanotechnology is going on for the best structure for QCL, preferred materials are InP and GaAs. Originally optimal performance could only be obtained at cryogenic temperatures due to currents in the order of 1 A and the corresponding heat dissipated in a small area. Efforts are going on towards operation at room temperature.

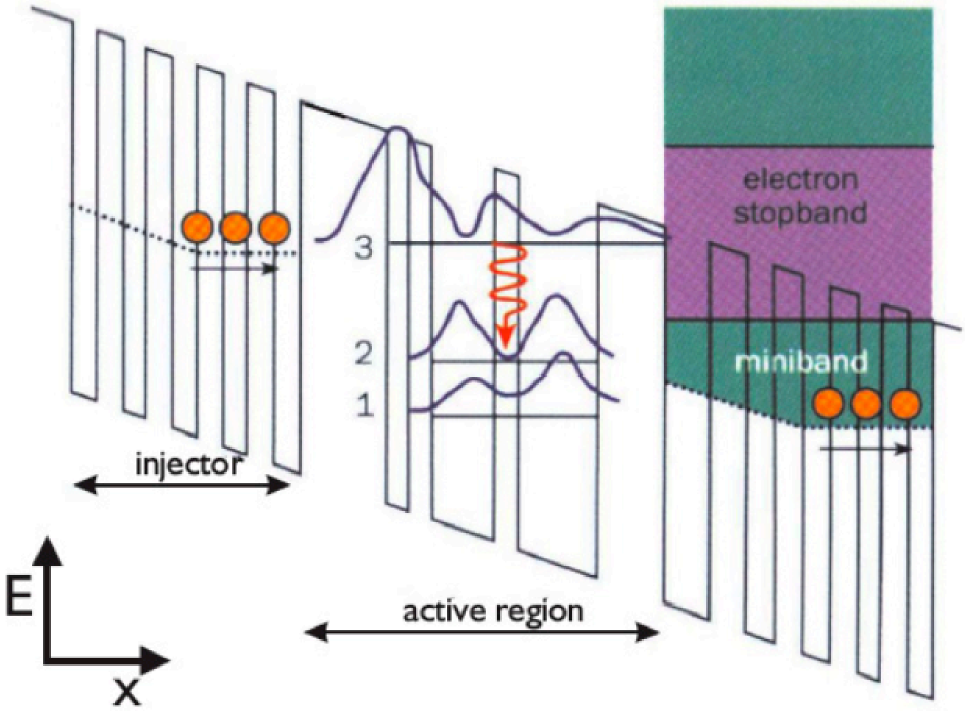

Figure 6. Working mechanism for a QCL. The electrons come from left and drift towards the right. Once they reach the active region, they stay for some time in the lower energy state of the left, narrow box (level 3) to decay by emission of a THz photon into the next wider box with ground energy about 100-200 meV lower than level 3. The electrons decay very fast to state 2 emitting optical phonons and setting free state 2 for the next electron to come. In this way a continuously empty state 2 causes an inversion of the carrier population with respect to state 3. This cascading of electrons gives rise to radiation in the terahertz region.

Figure 7 summarizes THz-emission power as a function of frequency. From all the sources broadly described above there are three major approaches for developing THz sources. The first is **Optical THz generation** which has experienced a major development in the last 10 years. The second approach is the recently developed THz-QCL, still being refined and whose projected operation at room temperature is not yet a reality. The third approach uses solid-state electronic devices which are already well established at low frequencies and they are entering the low frequency end of the THz regime.

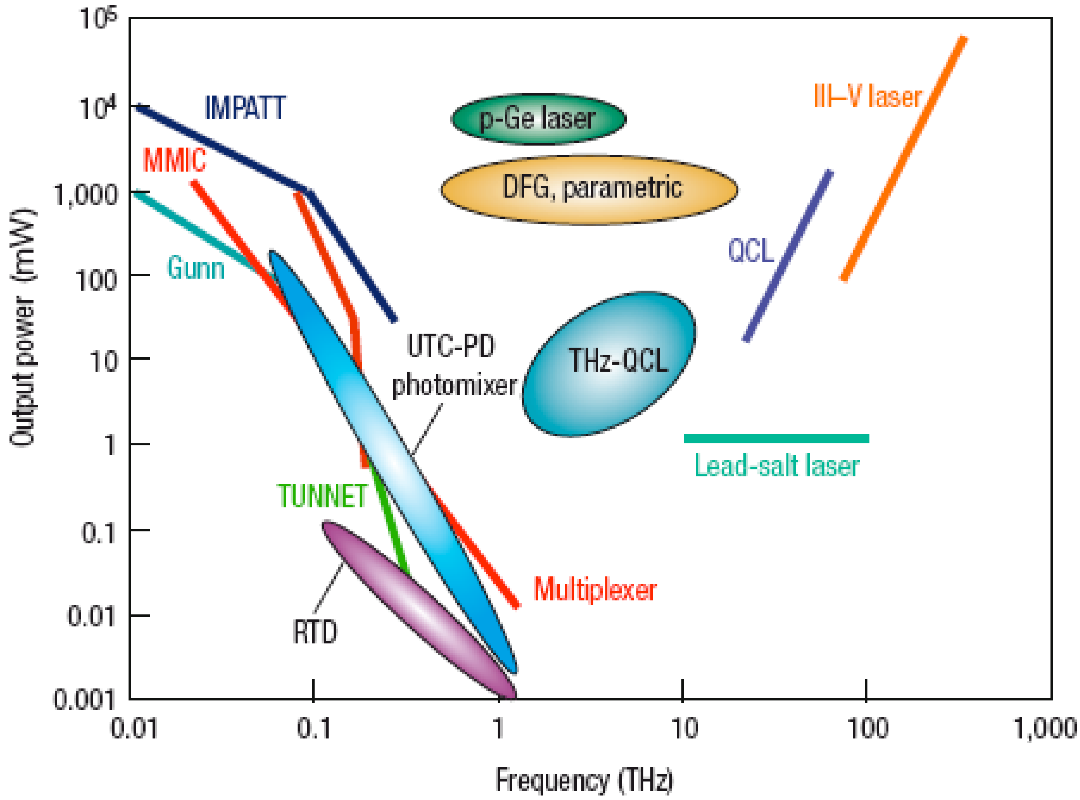

Figure 7. THz emission power as a function of frequency. Solid lines are for the conventional THz sources. Ovals denote recent THz sources. IMPATT diode stands for impact ionization avalanche transit-time diode, MMIC stands for microwave monolithic integrated circuit. TUNNET stands for tunnel injection transit time and the multiplexer is an SBD frequency multiplier.

A very promising electronic device is the UTC-PD (described in page 9). The emission is typically tunable up to 1.5 THz. Typical applications include sub-THz wireless communication.

2. Detection of THz.

The detection of THz frequency signals is experiencing an increase in research and development. The low output power of THz sources coming along with a relatively high level of thermal background radiation in the terahertz spectral range requires highly sensitive detection methods. The detection method is determined by the generation method. For broadband detection, direct detectors based on thermal absorption are commonly used. Most of these detectors require cooling to reduce thermal background. The most common systems are helium-cooled silicon, germanium and InSb bolometers, and pyroelectric infrared detectors.

For pulsed THz detection in terahertz time domain spectroscopy (THz-TDS) systems, coherent detectors are required. The two most common methods are based on photoconductive sampling and free-space electro-optic sampling, and these two methods rely on ultrafast laser sources. Fundamentally the electro-optic effect is the coupling between a low frequency electric field (THz pulse) and a laser beam (optical pulse) in the sensor crystal [19]. Photoconductive antennas are widely used for pulsed THz detection, in fact when the generation of terahertz occurs by means of an antenna, the detection will be best using an identical structure as the antenna used as the emitter.

In addition to these popular optical methods there are several electronics based detectors. Some of these detectors are: 1) heterodyne receivers based on GaAs Schottky diodes that have been developed for applications in the frequency range from 100 GHz to over 3 THz [20]. The high sensitivity, large spectral resolution, and large instantaneous bandwidth of these receivers have been used for a variety of scientific applications, including radio astronomy and chemical spectroscopy. It looks like these Schottky devices will continue to play a critical role at THz frequencies in the near future. The leader in commercial development today is Virginia Diodes, Inc. (US). However there are a number of effects that degrade the diode performance as the frequency approaches 1 THz. One of the most important effects is the increase in the series resistance of a given diode with frequency caused by the skin effect, which constrains the current to flow along the edge of the chip substrate. Furthermore, at THz frequencies the inertia of the electrons adds an inductive element to the circuit model, and dielectric relaxation adds a capacitive element. At a frequency of 1 THz, charges are moving on a timescale of 1 picosecond.

In the following section we will use some of the terminology described so far to enter into the development and projection of terahertz in the communication.

3. Projection in THz Communication

The term THz communication describes two subjects:

a) effective data rates exceeding 1 Tbit/s (usually on an optical carrier)
b) communication with a THz carrier wave.

There are several reasons why communications at THz frequencies are very attractive: one is the availability of the frequency band and the communications bandwidth. Frequencies above 300 GHz are currently unallocated by the US Federal Communications Commission (http://www.doc.gov/osmhome/allochrt.pdf). There is a window from 275 to 300 GHz reserved for communications. In Europe the allocation end at 275 GHz. Hence, there is free communication bandwidth above 275 GHz. Systems that work at these high frequencies already fall into the terahertz range.

Disadvantages of communications at THz frequencies are coming from the strong absorption through the atmosphere caused by water vapor as well as the low efficiency and relatively low power from currently available sources. For example for a 1 mW source and a detection sensitivity of 1 pW, the working dynamic range is 60 dB, which allows communications at a range of 500 m in an atmospheric transmission window with an attenuation of <100 dB/km. Figure 8 shows the atmospheric attenuation in the THz frequency range [8].

Despite the strong atmospheric absorption and low source efficiency, there are possible communications applications for this frequency range. For satellite-to-satellite communications, atmospheric absorption is not a problem unless the path grazes the Earth's atmosphere.

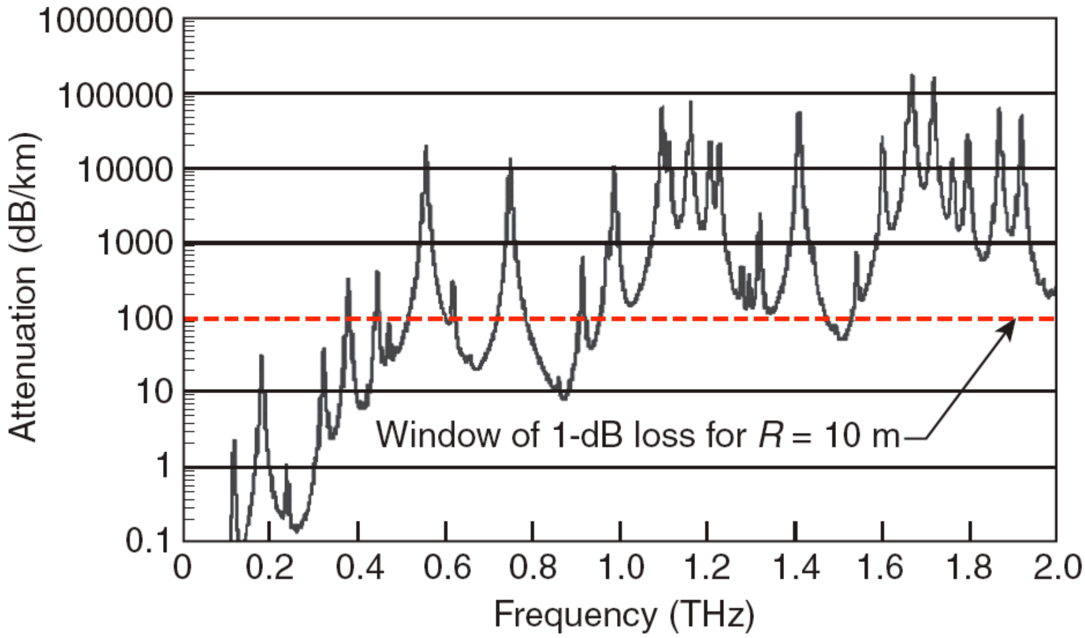

Figure 8. Atmospheric attenuation in the THz frequency range.

The advantage of using THz technology in this application is the larger bandwidth and consequently higher transmission rate as compared to microwave communications. The all-electronic conversion from the THz carrier to microwave links will be straightforward and at the same time, the size of the antenna will be reduced, which favors smaller satellite systems.

THz may provide multiple data channels with gigabit per second or more for indoor wireless communications.

One problem usually found in optical communications is attenuation caused by scattering and absorption by clouds, rain, dust, etc. In the Rayleigh scattering regime, the scattering cross section increases with shorter wavelengths as the 4^{th} power of the inverse wavelength. THz and millimeter waves experience much less scattering loss than optical wavelengths. Millimeter band communications can be used as a backup to an optical link in case of rain or heavy clouds. Similarly THz can be used for short distances if heavy particles like smoke or dust are present in the air.

Atmospheric transmission windows may allow application of THz for short-range tactical communication. In some cases, the limited transmission distance may be an advantage, if we consider the clutter and congestion of voice channels in combat zones [9]. THz signals are not far-ranging as they are heavily attenuated by free-space damping. Furthermore, THz links will have to be directed. Because of these two properties THz waves could provide secure links which would be ideal for a communication on the battlefield for example between tanks or individual soldiers (see figure 9).

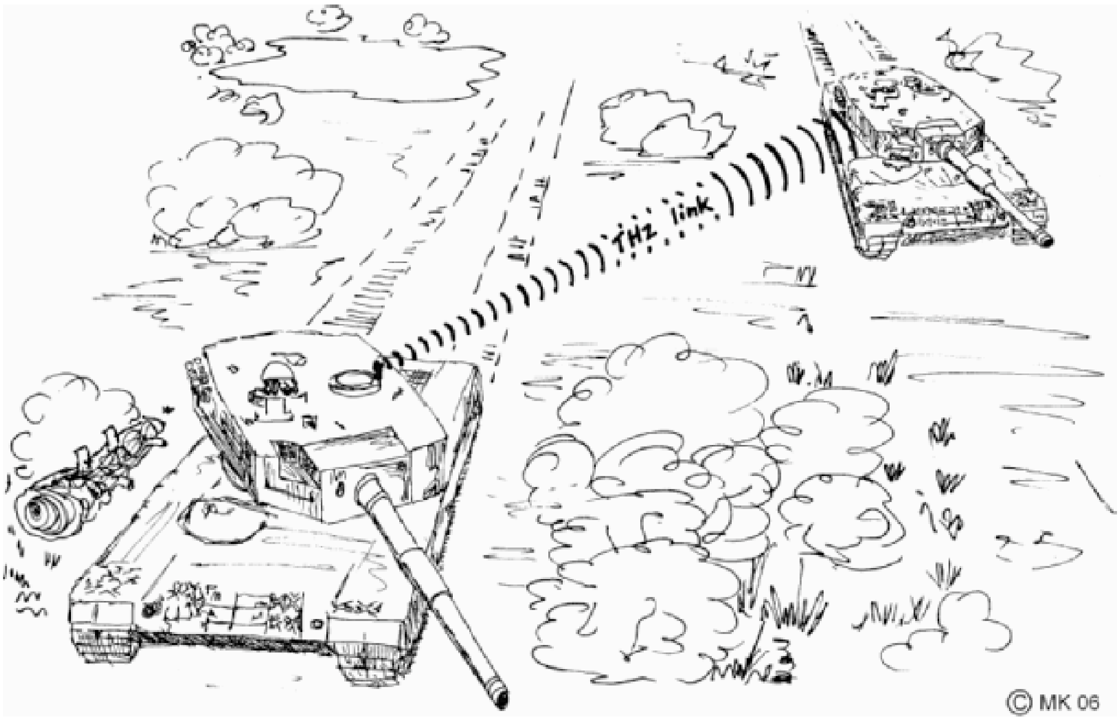

Figure 9. Secure THz link on the battlefield.

Frequencies of a few hundred gigahertz could be provided by **electronic sources**. There is a variety of compact classical microwave sources which can generate frequencies up to several hundred gigahertz some examples are: resonant-tunneling diodes, transferred-electron devices, and transit-time diodes. An even more practical method would be to multiply a lower frequency Gunn diode in a multiplier chain [10, 11].

4. THz Sources, Modulators and Detectors for Communication.

Sources:

1) As mentioned before the most appropriate sources of terahertz radiation in the communication area are electronic sources such as Schottky Diodes for which the leader in commercial development is a company called Virginia Diodes, Inc., in the US. These sources are based on microwave harmonic generation chains reaching 1.2 THz.
2) In addition there are vacuum tube technologies developed originally for radio and microwave applications, and they are now being extended to the terahertz frequency range. The most successful tubes is the backward wave oscillator (BWO), named like this because the direction of radiation amplification is opposite to the direction in which the electron beam travels. The disadvantages of this type of devices are: a) the need of a large external magnetic field, b) highly stable high-voltage power supply, c) it cannot be directly modulated thereby requiring a high-speed THz modulator or mixer.
3) Another THz source for communication applications is the QCL and has been described in a previous chapter. Active development aims to reduce the disadvantages which are: a) cooling at or near to nitrogen liquid temperatures, b) limited tuning range, c) limited device lifetime (hundredths of hours maximum), d) high costs. One interesting advantage is that QCL can operate in pulsed mode, allowing the possibility of modulating the output by directly modulating the injection current.

Modulators:

For future applications in THz communications and surveillance, several components will be needed such as: modulators, phase shifters, attenuators, and polarizers. A liquid-crystal phase shifter has been demonstrated [21]. It is difficult to adapt conventional electro-optic modulators because material birefringence is low in the THz regime. Modulation of a near-IR optical beam b a THz signal has been reported in an undoped double quantum well structure [22]. Semiconductor THz modulators have also been demonstrated but operates only at cryogenic temperatures [23]. A THz transistor has also recently been reported [24]. It is clear that a rapid progress is expected in THz devices.

Detectors:

As mentioned before heterodyne receivers based on GaAs Schottky diodes are becoming very popular in the range from 100 GHz to over 3 THz and will continue to play a critical role at THz frequencies (see page 12). There are other electronic devices such as resonant-tunneling diodes, transferredelectron devices and transit-time diodes with frequency range operation between 250 and 330 GHz.

5. Advantages of THz systems over Infrared or Quantum Cascade Lasers.

The natural question is why not to use directly near or mid-infrared frequency ranges to build communication systems for example to support data rates of several gigabits per second. For example the remote control of our TV set and wireless connections between a laptop computer and a printer work with infrared radiation.

There are several reasons that prevent wireless IR links from providing such high data rates. The modulation scheme at wavelengths of 880, 1310, 1550 nm is simply intensity modulation and the radiation is directly detected with a photodiode. This results in poor receiver sensitivity as compared to heterodyne detectors. In addition the ambient light noise at these wavelengths is significant. Therefore, the transmission of a symbol needs some time to exceed the noise level. To transmit higher data rates (i.e. a symbol in ashorter time) one would have to increase the signal intensity. This is not possible because of the existing eye-safety limit [25]. In addition this would also imply a higher power consumption this fact beinga serious drawback for battery powered portable devices. There is one publication addressing the possible use of IR radiation for short-range communication concluding that IR radiation seems to be unable to replace RF for indoor LAN applications [26].

On the other side of the spectrum, for wavelengths of several micrometers which is the domain of quantum cascade lasers the situation is not better: early QCL demonstrated in 1994 operated only at cryogenic temperatures, in pulsed operation and at mid-infrared wavelengths. Today mid-infrared QCL’s work in continuous wave and close to room temperature. In principle these devices are ready for industrial sensing and imaging applications. Unfortunately, no direct mid-infrared detectors exist which are sensitive, fast and work at room temperature. Heterodyne detection is possible but difficult. In addition the ambient light noise problem is even more severe here. Meanwhile there are some demonstrations of QCL's with working frequencies as low as 2.1 THz and 3.2 THz emitting continuous wave at 93 K [27]. Despite these advancements it is currently believed that THz QCL's will neither show emission at frequencies much below 1.5 THz nor work CW at room temperature in the near future.

There has been a recent demonstration from S. Hoffman and co-workers [28] of a single interband laser diode being placed in a special external resonator and forced to emit on two-longitudinal modes simultaneously emits THz radiation via a nonlinear process called four-wave mixing. The same scheme could be even more efficient for QCL's for their larger dimensions. This still has to be demonstrated however it is very well possible that two-mode QCL's will be used some day as short-range sources for indoor THz communications systems.

6. Conclusions

The development of technology to generate and detect THz radiation has seen incredible growth in the last 5 years. This is in part because of the great promise for security applications such as high-resolution imaging and spectroscopy or, for example, bio-agents or explosives detections. For these applications, much of the progress has been made using optically based techniques such as electro-optic generation or photomixing. Electric sources and receivers are now available for frequencies up to 1 or 2 THz, as are modulators that should allow communications in the THz frequency band to experience rapid progress. Even though the propagation length is limited, THz has some advantages like: small wavelength, high bandwidth, ability to penetrate dielectrics that become important in some areas over millimeter waves and optical free space communications.

There has been an important progress, however THz communications is still in its infancy. The application will define the type of source, detector, and material used in the terahertz technology. Development of better THz sources, detectors, and modulators is progressing, which will enable practical THz communications. We have given an overview of the state of the art for generation detection modulation and transmission of terahertz waves for communications application. The importance and relevance of terahertz for communications has been outlined with a simple analysis showing its advantages over infrared and quantum cascade laser radiation.

With the information obtained in the present period of the monitoring, several activities could be implemented in a near future. Some of these topics are:

a. selection of potential applications; indoor communication, outdoor communication-establishment of a “Terahertz link”,
b. available terahertz systems for identified applications,
c. transmission, absorption, materials parameters for the selected application(s),
d. what would be necessary to implement a terahertz system for a particular application,
e. definition of bandwidth, frequency spectrum, and signal to noise ratio,
f. demonstrator.

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