University of Sheffield
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Problem Solving in Physics

Terahertz Technology
an Overview

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Contents

List of Figures

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Abstract

New advances in different technologies have made the previously unused terahertz frequency band accessible for imaging systems. Applications run from detecting weapons concealed underneath clothing (airports), product inspection (industry), spectroscopy (chemistry, astronomy), material characterization (physics) to detection of cancer and caries. Most of these imply the use of terahertz imaging systems. This is such a new field that researchers around the world race to build the first practical system. This paper tries therefore not only to provide a brief overview over the imaging technology, but also over the whole range of current systems and research in terahertz technology.

1 Basics

The electromagnetic range that is used is very vast. At low frequencies end we have radio waves up to millimetre waves, and at the other end we have optical waves down to the far infrared. Technologies have been developed for both ends of the spectrum which we use in everyday applications. But the terahertz region:

$$0.1 - 10 \text{ THz} \quad 1 \text{ THz} = 10^{12} \text{ Hz}$$

with wavelength of 30μm to 3mm has remained largely underdeveloped, despite the identification of various applications, in particular Terahertz Imaging and others which will be discussed later on.

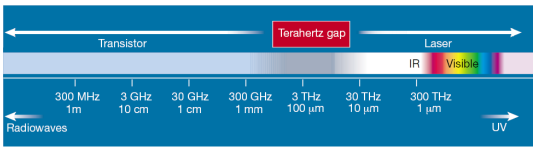

Figure 1: the Terahertz Gap (from Nature [1])

It is possible to produce effectively radiation in the low frequency region (microwaves) with oscillating circuits based on high-speed transistors and at high frequencies (visible spectrum) with semiconductor lasers. But transistors and other electric devices based on electric transport have in principle a limit at about 300 GHz, but are practically limited to about 50 GHz, because devices above this are extremely inefficient [1], and the frequency of semiconductor lasers can only be extended down to about 30 THz.
Thus there is a region in between where both technologies do not meet. This region is often referred to as the *terahertz gap*.

2 Sources for THz radiation

Till this day the lack of high power, portable, room temperature THz sources is the most significant limitation of THz systems.
For this reason this is a very lively research field. Some very promising new approaches have the potential to bring terahertz technology a step further to everyday applications. But these sources are still not fully developed technologies.
So this article tries to provide an overview over the currently used sources and these new approaches.

Further one in this section we divide between incoherent thermal sources, broadband pulsed (T-Ray) techniques, and narrowband continuous-wave methods.

Normal THz sources

THz radiation is naturally emitted by all bodies. The blackbody radiation in this spectral range, below the far infrared, is comparatively weak - lower than 1μW per cm^{-3}. Sources like light bulbs in the visible spectrum are therefore unsuitable.

Broadband sources

Following reference [2] most techniques are providing broadband pulsed THz sources based on the excitation of different materials with ultrashort laser pulses.
These are photocarrieer acceleration in photoconducting antennas, second order non-linear effects in electro optic crystals, plasma oscillations, and electronic non linear transmission lines.
Unfortunately most of the different technologies have very low conversion efficiencies (nano

to micro watts compared to about 1 W power from the optical source).

In the *photoconduction approach* a photoconductor (GaAs, InP) is illuminated with ultra fast laser pulses (with photon energy greater than the Bandgap of the material) to create electron hole pairs. An electric field of about 10V/cm is generated in the semiconductor by applying a DC voltage. Then the free carriers accelerate in the static bias field and form a short photocurrent. Because of the acceleration this moving electrons radiate electromagnetic waves.
According to [2] these photoconductive emitters are capable of relatively large average THz powers of 40 μW and bandwidths as high as 4 THz (see also references mentioned in the indicated article).
This source operates with comparatively low power, but the beam is stable and coherent with well known temporal characteristics. Hence it is used for spectroscopy with high spectral resolution and excellent signal-to-noise ratio and for imaging technologies.

Another approach is the *Optical rectification*. Here again we use ultrafast laser pulses, but we make use of the non-linear properties of materials. This means that the optical beam itself is the origin of our terahertz radiation. These non-linear effects arise when one illuminates a crystal with high intensities.
The required lower energy photons are achieved through a process called *down conversion*. This means that one incoming beam splits into two outgoing frequencies of lower frequencies. With the condition of conservation of energy ($\omega_{\text{in}} = \omega_{\text{out}_1} + \omega_{\text{out}_2}$) the output frequency is naturally not defined. We get therefore a range of frequencies. (for more information see for example [15])
According to [2] research in this field has focused in the past on materials like GaAs, ZnTe, and organic crystals.
This process provides terahertz radiation only with very low efficiency, but has the advantage of very high bandwidths. Frequencies up to 41 THz have been accomplished by one group (see therefore reference 23 in [2]).

First high power broadband THz source

Until recently there was no high power broadband THz source, but in [3] Carr *et. al.* describe a new method using energy recovered linacs[1] (ERL) at the Jefferson Laboratories[2] to accelerate electrons to relativistic energies.
As before this method begins with pulsed laser beams, but uses them for photoemission to create short bunches of electrons ($\sim$ 500 fs) in free space. The energy recovered linac brings these bunches of electrons to relativistic energies ($\sim$ 40MeV).
As long as the electrons travel in a straight line they do not emit light. After passing through the linac system the electron beam is diagonal accelerated by a magnetic field with a bending radius of 1m , which produces the THz radiation as synchrotron radiation.

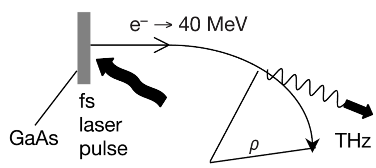

Figure 2: relativistic electrons diffracted by a magnetic field (from Nature [3])

This process produces coherent THz radiation with an average power of nearly 20 Watts, which is several orders of magnitudes higher than any other source.

Narrowband sources

The techniques under development range from upconversion of radio frequency sources to different kinds of lasers, including gas lasers, free electron lasers, and in particular quantum cascade lasers.

One technique to generate (low power) continuous wave THz radiation is through upconversion of lower frequency *microwave oscillators*. Frequencies up to 2.7 THz have been demonstrated[3]

Another common source are *gas lasers*. The

[1] linear accelerator
[2] Jefferson Laboratory Newport News, Virginia, http://www.jlab.org/
[3] see reference 26 in [2] for more information

gases used are mainly methanol and hydrogen cyanide. In this method a $C0_2$ laser pumps a low-pressure gas cavity with one of the gases mentioned, which lasers at the gas molecules emission lines.
These frequencies are not continuous tuneable and require large cavities and high (kilowatts) power supplies with only output power of the magnitude of milli Watts.

Extremely high power THz emission have been demonstrated using *free electron lasers* with energy recovering linacs.
Free electron lasers use a beam of electron bunches of high velocity propagating through a vacuum. This bunches of electrons pass a spatial varying magnetic field, which causes the electrons to oscillate and emit photons. Mirrors confine the electrons to the electron beam line to form the gain medium for the laser.
But such systems are huge in costs and size, and require often a dedicated facility. However they can generate continuous or pulsed waves with a brightness several orders better than any other source.

Another highly awaited source for THz radiation are *semiconductor lasers*. In the past these lasers have revolutionist applications in industry because of their small size, low costs, and high efficiency. Such a compact system for THz radiation is still missing.
The *first terahertz laser* was demonstrated over 20 years ago. This laser was based on lightly doped germanium at cryogenic temperatures under crossed electric and magnetic fields[4]. These lasers are tuneable through the applied magnetic field or external stress. But they have many inherent limitations such as low efficiency, low output power, and the need for cryogenic cooling.
Another approach to build semiconductor lasers in the terahertz region is based on the newer technique of a *Quantum Cascade Laser*. These lasers were first demonstrated in 1994.
A Quantum Cascade Laser consists of periodic layers of two semiconductor materials, which form a series of coupled quantum wells and barriers with a repeating structure. The wells and barriers are usually nanometer thick layers of GaAs between potential barriers of AlGaAs. Quantum confinement within the wells causes the conduction bands to split into a number of distinct sub bands[5]. By transition of electrons from a higher state to a lower state in the well light is emitted. As the difference between the energy levels is determined by the thickness of the layers, the produced frequency can be chosen by design of the layers.
Unfortunately these lasers operate only at very low temperatures. The energy spacing between the intersubbands is about $\Delta E \sim 0.004$ eV. Compared to room temperature $k_B T \sim 0.025$eV is this very small. This means that if $k_B T$ is not lower than ΔE electrons are exited into higher subbandstates. In a quantum cascade laser the subbands couple from the lower state to the higher state of the following unit. If the electrons are now all in upper states they cannot jump anymore through the stairs of the well structure and cannot be used for the laser anymore.
An interesting and very descriptive explanation of quantum cascade lasers can be found on the homepage[6] of the bell laboratories.

First Terahertz Quantum Cascade laser (Köhler et. al.)

In [4] Rüdiger Köhler and Alessandro Tredicucci of the Scuola Normale Superiore in Pisa and colleagues in Turin and Cambridge give a report on a Terahertz Laser build up with a Quantum Cascade structure. This article (2nd May 2002) attracted much attention in physics and science related magazines [1, 11, 12, 13]
As Köhler mentions in his letter in Nature [4] electroluminescence devices have been reported by several groups, but laser action had not been possible in THz wavelength before. Whereas they developed a laser, which emits a single mode at 4.4 THz and shows high output powers of more than 2 mW up to 50 K.
In [1] Sirtori C. summarises the problems that arise with a laser in the Terahertz region:
"Like other semiconductor lasers, Köhler's

[4] see reference 35 in [2] for more information

[5] see book [15] for more details

[6] http://www.bell-labs.com/org/physicalsciences/projects/qcl/qcl.html

device is composed of an active region and an optical waveguide that confines the radiation. But these two fundamental elements of a laser face complete different demands in the terahertz region. The main problems are the intrinsic optical losses induced by the free electrons in the material, the large size of the optical mode - imposed by the wavelength and the short lifetime of the excited state of the laser transition, in which the electrons accumulate to create the population inversions necessary for lasing."

This laser consists of 104 repetitions of the basic unit which comprises seven GaAs quantum wells (shown in figure 3) separated by $Al_{0.15}Ga_{0.85}As$ barriers with the active region consisting of three closely coupled quantum wells. The total structure consists thus of a total of over 700 quantum wells which were grown by molecular beam epitaxie (MBE).

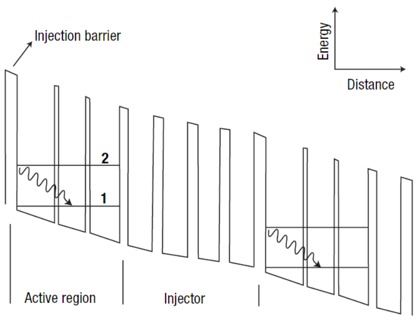

Figure 3: structure of Köhler's quantum cascade terahertz laser (from Nature [2])

More details about the layout and their approaches to overcome the problems with semiconductor lasers in this region (as mentioned) are available in Köhler's article in Nature [4].

These results are very promising although this laser operates only with cryogenic cooling. If they achieve to improve the design and can optimise fabrication, so that this semiconductor lasers works at liquid nitrogen temperatures, this would be a very significant improvement in terahertz technology.

3 Terahertz detectors

The detection of THz radiation necessitates very sensitive methods, as sources come with low output power and the thermal background radiation is comparatively high.

For broadband detection direct detectors are based on thermal absorption commonly used. These systems require cooling to reduce the thermal background. Systems common used are helium cooled silicon, germanium, and InSb *bolometers*.
Bolometers measure the incidented electromagnetic radiation through absorption and the resulting heating. The heating in turn is measured through the change in resistance. Extremely sensitive bolometers are based on the change of state of a superconductor such as niobium.

If high spectral resolution is required, *heterodyne sensors* are used. In these systems the frequency of interest is produced by a local oscillator and heterodyned with the external signal. The downshifted signal is then amplified and measured.

For pulsed THz detection in THz Time Domain Spectroscopy systems (see section 4) *coherent detectors* are required. The electro optic effect in birefringent crystals is used for the measurement of the THz beam.
The electric field of the THz radiation modulates the birefringence of the sensor crystal. This in turn modulates then the polarisation of the optical beam passing through the crystal. This modulation can be measured to find the amplitude and phase of the applied electric field.
Very thin crystals and very short laser pulses allow the detection of radiation in the THz region.

Photoconductive antennas are widely used for pulsed detection - the structure is identical to the photoconductive antennas earlier discussed (see page 2), but here the appearing current is measured.

4 Spectroscopy and Imaging systems

It should be mentioned here that one can manipulate THz beams with mirrors and lenses as with light in the visible spectrum, but different materials have to be used. These are opaque for our eyes, but transparent for THz radiation.
Two used materials are high resistivity silicon and high-density polyethylene. The former has no absorption or chromatic dispersion over the whole THz range, but has a high refraction index (≈ 3.42) and thus relatively large Fresnel losses. The latter has lower Fresnel losses, but has some small absorption above 1 THz, and a resonance at $\approx$ 2.2 THz [7].

According to [2] *Fourier Transform Spectroscopy (FTS)* is the most common technique for studying molecular resonances. With this technology one can characterise materials from THz to infrared frequencies.
The sample is placed in an optical interferometer and illuminated with a broadband thermal source. Of interest is the path length difference of one of the interferometer arms. The interference signal is then detected with an helium cooled bolometer. The Fourier transformation yields to the spectral power density of the sample. The main disadvantage of FTS is its limited spectral resolution.
If a much higher spectral resolution is required one can use a narrowband system with a tuneable THz source or detector.
This technique is used in passive systems for monitoring thermal emission lines of molecules, particularly in astronomy applications [2].

Another more recent technology is the *THz Time Domain Spectroscopy (THz TDS)*. This method of measurement is also termed *Terahertz Pulsed Imaging (TPI)* and as the name suggests the dominant method of imaging.
In this system the pulsed optical beam created by an ultrafast laser is splitted into a probe beam and a pump beam. The pump beam is incidented on the THz emitter (the THz source) to generate picosecond terahertz pulses. The terahertz radiation is collimated and then focused on the sample with parabolic mirrors. After transmission through the target the beam is collimated and refocused on the THz detector.
The detectors used for TDS are described in section 3. These detectors can measure the electric field coherently.
The optical probe beam is used to gate the detector and to measure the THz electric field instantaneously. At this the optical delay stage (computer controlled) is used to measure the transmitted terahertz pulse profile at a discrete number of time points to provide temporal information.
Figure 4 illustrates such a system.

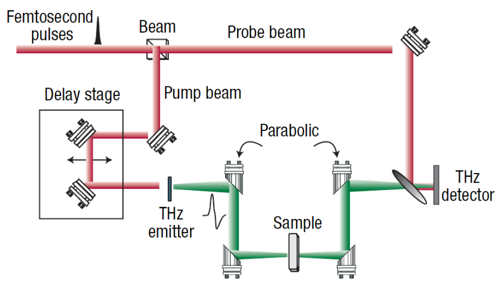

Figure 4: Illustration of a THz-TDS system (from Nature [2])

Following Ferguson B., Zhang Xi-Cheng [2] has this technology disadvantages compared with Fourier transform spectroscopy described before. They say that the spectral resolution was worse than with narrowband techniques and its spectral range much less than of FTS, but it had some other advantages that made it so important: The transmitted electric field is measured coherently. Therefore high time resolved phase information can be received.

5 Terahertz Imaging

Terahertz Imaging or also called *T-Ray Imaging* is based on time domain spectroscopy (TDS). The possibility to detect the radiation coherently makes it possible to record not only the intensity, but also the time resolved amplitude and phase of the electric field. In turn this leads to the possibility of obtaining a spectrum by Fourier transformation of the time domain signal.

In article [8] from the Center of Medical Imaging Research (CoMIR) is reported that *Fourier transformation* methods have been used to access the spectral information from the time domain signal, but these are not capable of addressing temporal information of frequency components.
Alternatively *wavelet methods* are used for the broadband THz pulses. These provide additional information about the temporal information of spectral content.
Wavelet methods are based on different mathematics, compared to Fourier transformation. Their original purpose lies in the field of image compression. More information about signal processing algorithms used in this field can be found in [9], which seems to be from CoMIR as well[7].
Images are obtained with THz-TDS by spatial scanning of the object for imaging. This is performed by using raster scanning of either the terahertz beam or the sample itself.
An imaging system in which the beam is reflected off of the sample, rather than transmitted can be used for *tomographic imaging*. This means that the regions of reflection in the sample are measured. This is possible because the arrival time of the reflected THz waves can be determined with an accuracy of a few femtoseconds. This is less than the pulse duration, so the positions of reflecting surfaces can be determined with an accuracy of few micrometers, but under the condition that successive reflections are well separated in time [6].
The applications of tomographic imaging are later discussed under applications on page 8.
D.M. Mittleman says in [7] about THz-TDS imaging: "Because THz-TDS does not require any cryogenics or shielding for the detector, it has the potential to be the first THz imaging system that is portable, compact and reliable enough for practical applications in »real-world« environments". (As described in section 3, the detectors measure an optical beam and thus do not need any kind of cooling).

[7] This paper seems not to be officially published

6 Properties of THz radiation

THz radiation has some properties that open a wide range of applications, particularly for imaging. On the other have materials very interesting properties in this frequency range:

Compared to microwaves, THz waves have more energy so they can penetrate deeper and make sharper images due to their shorter wavelength. Additionally it is expected that terahertz frequency radiation should be scattered less than visible and near infrared frequencies, as the amount of Rayleigh scattering decreases with the fourth power of the wavelength.
If one will illuminate materials with THz radiation they will show these characteristics:
Polar liquids absorb strongly in the terahertz band. An example of such a liquid is water.
Metals are opaque to terahertz radiation, whereas non-metals such as plastics, paper-products, and non-polar substances are transparent. Dielectrics in constrast have characteristic absorption features peculiar to each material.

Water sensitivity

According to [5] the minimum detectable water concentration is given by

$$n \cdot x \sim 10^{16}\text{cm}^{-2}$$

n is the density of water molecules and x is the length of the path traversed by the terahertz beam in the material.

Safety / Medical implication

Implications on living tissue are not expected as T-Rays are non-ionising in contrast to x-rays or ultraviolet (UV) light. Moreover, Terahertz signals are strongly absorbed by water, so that terahertz radiation cannot go through living tissue because of the high percentage of water in it.
The article [9] nevertheless warns that it should be taken into consideration that there is also the possibility of thermomechanical and thermochemical effects for the pulsed radiation used in terahertz pulsed imaging (TPI)/(TDS).
A project[8] that works on this issue is called

[8] http://www.frascati.enea.it/thz-bridge/

»THz-Bridge«.

Theoretical prediction of water absorption

On one homepage of CoMIR[9] [10] the scientists say that preliminary measurements on tissue penetration have showed that predictions of attenuation based on water content alone have been incorrect.
This group wants to develop a theoretical model for the absorption of terahertz radiation and compare the results with experimental measurements.
So their work will show how safe the use of THz imaging is for living tissue.

7 Applications

We use x-ray scanners to examine luggage. Hospitals are equipped with ultrasound scanners and MRI (magneto resonance imaging) machines. In industry x-rays are used for package inspection and materials can be scanned for defects with microwaves or ultrasound. But although these technologies are very successful they all have shortcomings.
In some cases these old techniques can be replaced by THz based methods, but there are also applications, which are unavailable with other frequencies, but possible with THz due to the characteristics of the materials as described before.
Hence, many possible applications rely either on the extreme sensitivity of water or the ability to propagate through common packaging materials or both.

The list of possible applications is quite extensive. Therefore, the examples of applications showed here are only a cutout and not a complete list:

polar molecules

With THz radiation one has the ability to detect and identify most polar molecules in the gas phase. This application requires THz radiation with broad bandwidth and relies on the fact that, as in the mid-infrared, many molecules have characteristic "fingerprint" absorption spectra in the terahertz region. [5]

[9] Center of Medical Imaging Research

For these reason it was astronomy in the past, which required research in the THz field because of the huge amount of information available in space through THz radiation. [2]

material characterization

For physics this new technology is very interesting because they can use it for characterization of materials like semiconductors and lightweight molecules. The radiation can be used to determine the carrier concentration and mobility of semiconductors[10], and in the superconductor research it can be used to determine the parameters of superconducting materials. (See the article [5] from Mittleman for a description of the physics behind material characterisation with THz radiation).

quality control

THz imaging systems are ideal for imaging dry dielectric substances including paper, cardboard, thin wood, most plastics and ceramics, because these materials are relatively nonabsorbing in this frequency range. And additionally, these materials cannot be analysed with optical frequencies, because they are opaque for them or with x-rays, which have no absorption to provide contrast for imaging. Therefore spatially resolved transmission measurements can be used in the area of quality control of packaged goods, if the packaging consists of one of the transparent materials listed above.
In many industries x-ray imaging is currently used for such tasks. T-ray imaging is thus a desirable alternative because of the health and safety issues involved with ionising radiation.

The sensitivity to water is important here as well. To measure the water content of moisture sensitive products exist various methods, but these are not applicable if the content is in a cardboard or a plastic package. Obviously, THz radiation is predestined to be used here.

D.M.Mittleman reports in his papers [5, 7] about various experiments in the field of quality control applications.

[10] see references 48-50 in [2] for more information

study of historical and archaeological work

Terahertz imaging methods work with extremely low powers, about 2 to 3 magnitudes of order lower than the blackbody radiation in this frequency range. The radiation is therefore non invasive to historical work, neither to paintings or paper in common nor to any kind of stone or metal. Thus this technique could be useful in history, archaeology etc.
In [7] D.M.Mittleman discusses the possibility of using THz imaging for the investigation of underdrawings beneath paintings. This could be an excellent complimentary technology to the mid infrared and x-ray based imaging systems currently used for such studies.

biology (botany)

This extreme sensitivity to water content is of great interest here as a method of measuring the water content of leaves on living plants. Currently there is no accepted non-destructive procedure for measuring the leaf water status of a transpiring plant. [5] (see figure 5 as an example)

Figure 5: watercontent based image of a leaf (from IEEE Journal [5])

The cellular structure can be studied with THz as well. But a fundamental limit here is the resolution of current systems [2].

biomedical

In the area of biomedical diagnostics we can make use of THz tomographie. Although there is a limited penetration depth of the radiation due to the strong water absorption, which excludes the use of THz radiation in most biomedical research areas, it can be used to examine tissue near the surface, in particular skin and teeth. On the other hand, the sensitive to water enables the investigation of tissue hydration.
This opens a range of applications including analysis of burn depth and severity, and detection of skin cancer and caries.
A reliable non-invasive probe of burn depth would be of great value to physicians, who currently have no such technology. In [7] simple experiments are explained which test the use of T-Rays for this application.
The detection of skin cancer works very well although from the medical part not very well understood yet [14]. It seems that the cancer cells have a distinct different proportion of water compared to healthy cells, so that simply the higher absorption due to the water is measured. Breast cancer detection could be an application as well, because of the lower water content of the tissue there.
The detection of caries is another possible application. But there are still problems with the imaging technology which have to be solved before this is ready for application.
An overview over the imaging techniques and their problems with tooth imaging as one example can be found in [9].

security checks (Airport)

At airports or other security critical places dangerous non-metallic substances like ceramic knifes or plastic explosives now can be detected with terahertz beams. This is possi-

Figure 6: terahertz image of men with hidden knife (from Spiegel Online[14])

ble because T-Rays get through clothes, but cannot get through the upper skin (because of the water content). Figure 6 illustrates very clear how effective this imaging method works[11]. The British company Qinetiq has tested such a system on airports already [14]. A picture[12] of their camera can be seen on their homepage. This picture is similar to the one shown here.

8 Commercial Products

Many of the systems in use for research are laboratory based and occupy an area of a few square meters, but more compact and portable systems are under development.

An example is the product from TeraView Ltd., Cambridge, UK (www.teraview.co.uk) which is a prototype reflection system for use in dermatology. They launched their product in July of 2002. Teraview is a start up spun out of Toshiba's Cambridge research laboratory.

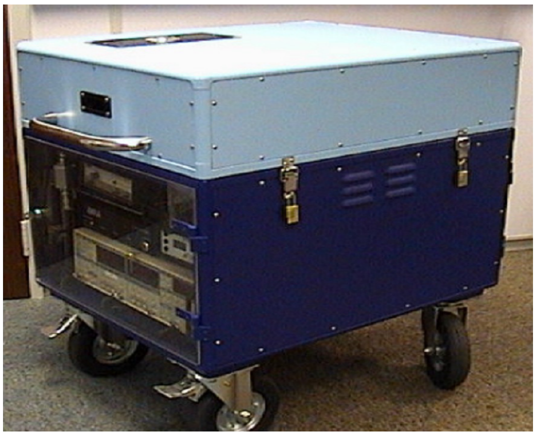

Figure 7: Teraview's prototype »TPI-Scan« for medical imaging (from Article [9])

Another commercially available system is the T -Ray 2000 by Picometerix[13], Ann Arbor, Michigan USA.

[11] Unfortunately is on this webpage no original source for this image specified. The authenticity of the image can therefore be querified.

[12] available on: www.qinetiq.com/technologies/sensors/

[13] www.picometrix.com/t-ray/

According to [9] there is another system under development by the Zomega Technology Corporation. An announcement can be found on a homepage[14] of the Army Research Office (USA).

9 Conlusion

The applications mentioned here show that THz imaging is desired by many different parts of industry and research, so that it can be expected that much efford will go into this field.

But despite the number of potential applications for THz imaging no technology is yet the ideal way, though the recent advances could lead to practicable and compact systems. Hence, reasearch in this field is going to be very lifely and interesting in the future.

[14] www.arpo.army.mil/arowash/rt/sttr/st992abs.htm

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