Terahertz-Technology: Quo Vadis?

Martin Koch, High Frequency Technology Institute, Technical University of Braunschweig, Germany

In the last few years the terahertz (THz) frequency range has enjoyed increasing interest, in particular in the media. In the course of this coverage a multitude of applications have been discussed for THz systems, ranging from medical diagnostics and security applications to industrial control processes. In these application fields THz imaging techniques stand at the focus of current interest. In addition, “in-door” communication with THz waves promises to be a mass-market by 2015.

The fundamental technologies underlying these applications are diverse. Imaging techniques utilise microwave-based THz cameras as well as broadband systems employing short, optoelectronically generated and detected THz pulses. Modern astronomy makes use of very sensitive detection methods for locating interstellar matter in the universe, but as these are based on so-called “hot electron” bolometers or SIS (superconductor-insulator-superconductor) mixers, the major drawback preventing their mass application is the fact that they must be cooled to a few degrees above absolute zero. And in terms of efficient THz generation, the quantum cascade laser (QCL), an intraband semiconductor laser with a complicated layer structure, seems to be a promising candidate.

Although it is impossible to cover the full breadth of terahertz technology in only a few pages, presented here is an overview of the most important applications relevant to industry. In the course of this overview we will also discuss and critically evaluate the potential of terahertz technology for the various application areas.

1 Importance of the THz frequency range

Terahertz waves can be regarded either as short wavelength microwaves or as long-wavelength light, with a frequency range reaching from 100 GHz to 10 THz (see figure 1). Although all other areas of the electromagnetic spectrum are used in current technologies, development in the THz region is still difficult. The reason for this lies in the lack of efficient, affordable, and compact THz transmitters and receivers. Although difficult, it was not impossible to conduct THz experiments in the past. These experiments appeared mostly under the label of far-infrared spectroscopy, with the first THz material investigations already having been performed by the middle of the last century.

Yet, it is indisputable that in the last couple of years significant progress has been made in the area of THz devices. To illustrate the recent increase in research activity, figure 2 shows the number of hits in the SPIN database when searching for the key words “THz” and “terahertz”. But what makes the THz frequency range so interesting and what market applications exist for THz systems? The answer to this question is manifold. Primarily there are scientific questions which can only be answered with a mature THz technology. Spectroscopic investigations dominate here, whereby the investigated phenomena can be quite diverse, ranging from rotational transitions of polar molecules in the gas phase to vibrational modes of crystals and biological macromolecules. The dynamics of structural changes in the molecular network of fluids also falls in the THz frequency range. Additionally, there are investigations of structured metal films, plasmas, and superconductors.

The investigation of fundamental physical mechanisms thus provides a steadily increasing but still manageable number of THz research groups with their right to exist, and the research carried out by these groups results in a multitude of interesting scientific publications.

Figure 1: The electromagnetic spectrum

Figure 2: The growth of terahertz publications from 1986 until today
2 Markets for THz imaging systems

These small scientific applications contrast with the various commercial markets for more practical applications that are predicted to develop in the near future. One of these proposed markets is for THz imaging systems, and it is itself composed of differing application segments, being coarsely divided into passive and active transmitter-detector systems.

Passive systems are receiver arrays, which can be seen as a sort of THz camera and which are generally based on highly developed microwave technology at a few hundred GHz. For instance, such passive arrays are developed for military purposes, being used to detect hostile targets even under bad weather conditions. In the civilian sector there are also applications for this technology, such as a landing aid for aircraft. Ordinary sunshine provides the essential THz illumination during the day, but when the system is used inside or at night, an artificial THz source is needed to provide the necessary illumination. The THz system would consequently become an active system complete with transmitter and receiver. In the case of microwave-based systems, one speaks of synthetic aperture radar.

While water-containing objects like the human body are impenetrable to these cameras, THz waves do have the capability to penetrate most textiles, especially in the frequency range of a few hundred GHz. It is thus possible to use these THz cameras in security related fields, such as inspecting airline passengers for weapons or explosives.

Although the quality of these pictures isn’t at present ideal, they can nonetheless detect concealed and suspicious objects on a fully clothed individual. At present, several companies are intensively developing this type of security camera, and government funded research institutions such as the Berliner DLR are also active in this field. Led by Dr. Hübers within the framework of the European TeraSec project, this group of researchers aims to develop a THz camera with the ability to provide useable images of a person at a distance of 25 m. This distance provides a sufficiently large safety margin against a potential terrorist carrying explosives. As the requirement for additional safety measures in the aftermath of September 11, 2001 has grown, it seems indisputable that we will experience this technology first hand in only a few years time. An issue remains in that the individual under examination appears more or less unclothed in the image, thus raising the possibility of acceptance problems associated with the technology. A solution may be that THz image evaluation will be undertaken by a computer program - in contrast to the x-ray examination of suitcases, which are always inspected “manually”. Nonetheless, it can be reliably expected that a significant market will develop for THz camera systems for military and security applications.

Thus far we have discussed a potential application for microwave-based systems, which frequency-multiply the output of a Gunn element or other microwave diodes in a chain of mixers and thereby generating THz waves in the frequency range from 100 GHz to around 1 THz. Another type of active THz system generates and detects THz waves optoelectronically through utilisation of a laser and a photoconductive dipole antenna. In this instance one must differentiate between continuous-wave systems and systems that generate broadband THz pulses. Only the latter will be discussed in the following section.

3 Technology and markets for pulsed THz systems

The core component of a pulsed THz system is a femtosecond laser, the pulses of which are used to drive photoconductive dipole antennas. These antennas consist of a piece of gallium arsenide onto which two parallel metallic conducting strips have been deposited. The laser pulses generate electron and holes between these strips, these then being accelerated by an applied electric field. The resulting short current pulse is the source for a THz pulse radiated into free-space (figure 3).

In an active optoelectronic THz system, one antenna acts as THz transmitter and a second antenna acts as receiver. An alternative to the antenna technology is the use of nonlinear crystals.

In either case, the THz pulses are detected time-resolved, which gives rise to several advantages. On one hand their frequency content can be analyzed, leading to a determination of the complex dielectric function of materials and thus too of the THz absorption coefficient and refraction index. On the other hand, and by drawing a suitable analogy to ultrasound systems, the reflection of THz pulses at any internal surface can be recorded, thus revealing detail of the inner structure of the object under examination. By comparing two appropriate reflections, this method can be also used to determine the spatial thickness of an object. An example is given in figure 4, showing the safety cover of an automotive airbag. In the photograph one can easily trace the lines where the material is thinner, and it is along these lines that the safety cover will break open and the airbag will spring out. The thickness of the material is a critical element to proper operation. If the material forming the break line is too weak, the safety cover can be accidentally damaged and this can lead to complaints about poor material quality. If the material is too strong, the break will not occur properly and the entire safety cover may be blown off at full force and injure the occupant. As the airbag and safety cover form a part of the car’s security system, the best possible compliance with the tolerance requirements is crucial. For this sort of application a non-destructive, non-contact, but reliable test method for checking the material thickness is desired, an end-goal being a 100% quality control inspection of each manufactured unit.

In the THz image in the right portion of figure 4, the break line can be clearly
observed. The material strength can be evaluated by using the peak position of the THz pulses. Figure 5 shows (black) a THz pulse travelling simply through air. The blue trace shows a pulse that has propagated through an area of the safety cover next to the break line, while the red trace shows the pulse after propagation directly at the break line. This latter curve has two signal peaks, the smaller of which being relevant here. Through comparison of this with the black curve, the material thickness can be precisely measured. This example also illustrates how a THz system can be used to determine the dimensions of complex injection-moulded parts. In particular multi-layered structures containing air layers can be accurately examined, a task that is difficult for ultrasound.

A second application area in the polymer industry is the quality control of compounding processes, by which the physical properties of polymers are altered by the addition of additives or fillers. Figure 6 shows a THz transmission image of a test sample made of polypropylene and Mg(OH)$_2$, an experimental flame retardant. The dark-blue areas show regions of reduced transmission where the Mg(OH)$_2$ particles are clumped together to from agglomerates. In principal THz spectroscopy should be an ideal tool to monitor the degree of dispersion, i.e. if the additives are homogeneously distributed. This monitoring could be performed inline.

Other industry applications are to be found in the quality control of sweets and wood products, or an inspection for proper filling and sealing of packaged products. In addition, mail or luggage can be inspected, where the initial goal in this application is simply to locate suspect materials. After an initial sorting of suspect from non-suspect post, a subsequent detailed analysis of the material then serves to differentiate between e.g. anthrax spores and backing soda.

Another application that has attracted considerable attention from the media is clinical diagnostics. As THz waves cannot penetrate more than a few hundred micrometers of human tissue, their use is restricted to an investigation of the body surface. In a study, unfortunately not published in great detail, it was shown that pulsed THz imaging can distinguish between basal cell carcinoma and other skin irregularities. Unfortunately, and despite the results of this study, the interest shown by dermatologists has remained low due to the high price of pulsed THz systems. The reality is that dermatology clinics and practices are not prepared to invest a large amount in a technology that only brings limited additional dermatological information.

Although THz images of teeth have been often seen in the press, these were mostly obtained from extractions that were cut in slices and then dried. The reality is that living teeth in a jaw cannot be penetrated by THz waves, as the water content is too high. The net result overall is that it is doubtful whether a significant market potential exists in the area of medical diagnostics.

Nonetheless, the strong market potential of optoelectronic THz systems in the other applications discussed above should not be dismissed. Worldwide, an increasing number of companies are striving to bring this technology to the market. As the price of these systems is principally determined by the costly femtosecond lasers and is thus still quite high, the number of systems actually sold to date is still small. Critically, THz systems have to become much faster for many of the applications discussed. The images shown in Figures 4 and 6 were obtained with our laboratory system over several tens of minutes. The chocolate industry, however, requires one chocolate bar to be inspected in 0.1 seconds, which corresponds to a translation speed of 2m/s. A similar imaging speed is also required by the polymer and wood industry.

Our research in Braunschweig is currently focused on achieving these imaging speeds and also on making THz imaging systems more cost-effective. Our preliminary tests have shown that the stipulated measurement speeds can be met.

4 A future mass-market: in-door-communication

Besides their use for imaging, THz waves hold an enormous technical potential as carrier waves for wireless networks. There is a steadily growing demand for short-range wireless bandwidth in current society, and if one looks at the exponential growth of bandwidth usage in the last 30 years, the projected bandwidth requirement 10 years from now will be roughly 14 Gigabits per second (Gbps). This is well out of reach of current Bluetooth wireless local area network technologies, both of which work with carrier waves between 2 and 5 GHz. In the not too distance future, we will undoubtedly see local transmission networks working with carrier frequencies...
in the 50-60 GHz range. In the long run, these carrier frequencies will increase further and enter the THz frequency region. Systems that work in the 200-300 GHz range appear feasible within just a few years time. However, a lot of research work is still needed in order to develop small, reasonable cost, and effective transmitter and receiver components at several hundred GHz. The use of this high frequency in local transmission networks would make a broadband system of several tens of Gbps possible. One vision, for example, is for one hundred or more conference participants sitting together in a conference room and all being wirelessly connected to the internet simultaneously at video data rates. It will surely take 10 or 15 years before this becomes a reality.

Japan has identified THz technology as key technology and has raised millions of Euros towards terahertz research. Importantly, if Germany doesn’t want to be caught by surprise by the likes of USA, Great Britain and Japan when this technology hits the market then the funding of terahertz research needs to be significantly increased.

Acknowledgments

I would like to thank Frank Rutz, who took all of the THz images in this article, as well as the BMBF, the AiF, and the EU for their financial support of our research in multiple projects. The polypropylene sample was provided by the Süddeutsche Kunststoffzentrum.

References:

Author contact:
Prof. Dr. Martin Koch
Institut für Hochfrequenztechnik
Technische Universität Braunschweig
Schleinitzstr. 22
38106 Braunschweig
Germany
Tel. +49/531/391-2000
Fax +49/531/391-2045
eMail: martin.koch@tu-bs.de
Internet: www.tu-bs.de/ihf/ag/terahertz