Terahertz Technology and Its Applications

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Abstract

In this paper we review the recent progress of terahertz (THz) technology and its applications in various fields such as THz sensing for bio, medical, medicine, security and others.

Keywords: THz technology, THz spectroscopy, THz sciences.

Introduction

The term ‘T-rays’ was coined in the early 1990’s by Bell Labs to describe the spectrum in the Terahertz range (1 THz = 1012). [1] The terahertz region of the spectrum lies on the border of where electronics and optics meet between the mm-wave and infrared bands (100 GHz-10 THz). THz wave could handle ultra broad band signals , have very large absorption due to water or water vapours and are transparent through many materials (e.g. plastics , papers, cloth and oil) that are opaque in visible and IR light. Many materials have a so called fingerprint spectrum in the spectrum range therefore terahertz wave are expected to be applied to ultrafast wireless communications, scanning systems of hazardous materials and assay devices for medical examinations. They are also expected to be applied to the multiresidue analysis for agrichemical, medical diagnostics, environmental assessment, process monitoring system for industrial products and biometric security. There is an atmospheric prevailing that terahertz technology represents the drawn of a new era.[3]

Applications

Overview: **-** The terahertz regime is sandwiched between the microwaves and the infra-red, bridging the gap between electronics and optics. Due to this exposed position in the electromagnetic spectrum, a plethora of metrological applications with high impact on a variety of industries exists. Even though the terahertz (THz) frequency range (0.1 THz to 10 THz) it has proven to be one of the most elusive parts of the electromagnetic spectrum.[2] For a long time, the THz regime was also referred to as the “THz gap” as neither optical nor microwave devices could fully conquer this shadowy domain with its many hidden scientific treasures. Little commercial emphasis was placed on the development of THz systems as the available sources, such as synchrotrons, backward wave oscillators, Smith-Pur-cell emitters or free electron lasers, were very costly components.[4] The numerous potential THz applications, ranging from medical imaging, security scanning and process control to ultra-fast communications, lead to a rapid development of THz systems and today first THz products are on the brink of large-scale market introduction. THz applications cover different industrial fields, illustrating the broad applicability of THz technology.

THz for the Polymer Industry

Despite the fact that polymers are a relatively young group of materials, they already managed to overhaul steel, the all-time favourite construction material, in terms of production volume. Many plastic materials are transparent to THz waves, so that they are commonly used as base material for THz optics, serving as inexpensive system components.[5] THz is returning the favour by providing an extensive set of quality inspection tools, often superior to existing measurement methods.

Dispersion Quality control for Polymeric compounds

Most technical plastics consist of a base polymer loaded with fine additive particles, which allow to custom tailor the functionality of the material. For example, the colour, the flammability or even the mechanical properties can be adjusted by com-pounding. However, in- or online monitoring of the dispersion quality achieved in such compounding processes is a challenging task. Here, THz technology can provide a valuable contribution.

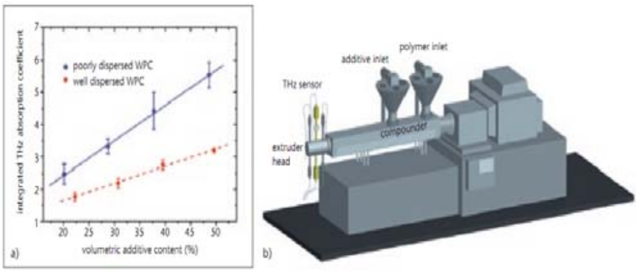

Figure 2.1 : Dispersion quality measurements on wood plastic composite samples

Figure 2.1 a) shows offline measurements of the absorption co-efficient of well and poorly dispersed wood plastic composite (WPC) samples, integrated in the frequency range between 0.2 and 0.8 THz over the additive content. The absorption rises towards higher concentrations of the wood particles, as wood is less transparent to THz radiation than the base polymer (polypropylene), and due to the fact that the number of scattering centres increases.[7] Latter aspect is also responsible for the stronger absorption in case of the poorly dispersed WPC samples. In Figure 2.1 b), an application scenario is depicted. At the outlet of an extruder unit, a THz sensor head is installed, delivering the required data for the evaluation of the dispersion quality.

Plastic Weld Joint inspection

As plastic continuously replaces more expensive materials like metal or ceramics, the demands on the joining technology for plastic components are steadily increasing. Especially important is the plastic welding, which, if applied successfully, forms a stable physical bond. For example, high-density polyethylene pipes for gas and water transportation rely on this technology and any defect in the weld joint is associated with high costs and risks.[4] Non-destructive testing of plastic weld joints seemed to be a permanent obstacle. X-rays and ultrasonic waves were not able to satisfactory identify inclusions or delaminations and the only means of obtaining low failure rates was the careful monitoring of the welding process parameters.

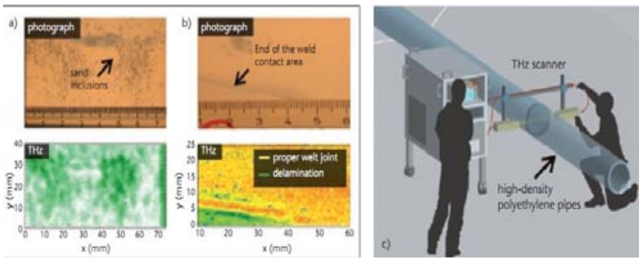

Figure 2.2 : Photographs and THz images of plastic weld joints

Initial measurement results for a weld joint with dielectric inclusions (sand) and a weld joint with a delamination are shown in Figure 2.2 a) and b) respectively. The THz waves clearly reveal both defect types – contact-free and non-destructive. The final system should be a mobile unit, which can directly be employed at the places where the weld joints are created. Figure 2 c) illustrates our vision for such a system.[3]

Fiber Reinforced Plastic composites

Another class of polymeric materials, which can benefit from THz technology, are fibre reinforced plastics. Here, the mechanical properties of the component are directly connected to the fibre orientation. Again, non-destructive testing methods are extremely rare and limited to specialized cases.

As the orientation of the fibers inside the host medium directly results in a birefringent behaviour of the composite material for sub-mm waves, THz technology can be employed to identify the fiber orientation.[2] While carbon fiber composites are strongly absorbing, so that the measurement options are limited to reflection geometries, glass fiber composites are fairly transparent to THz waves and can be analyzed in a transmission configuration.

Inspection of Safety critical components

Some polymeric components are employed in safety critical places. For example, plastic airbag caps commonly used in passenger cars. A thin grove serves as predetermined breaking line, where the cap is supposed to crack in case of an accident. However, the cap should withstand other non-critical physical impacts. Thus, the functionality of the cap depends on the correct grove depth of the predetermined breaking line. Controlling this thickness is not easily accomplished as ultrasonic measurements do not yield a resolution in the µm range. THz imaging can be employed to accurately determine the grove thickness by measuring the propagation delay of the THz pulse.

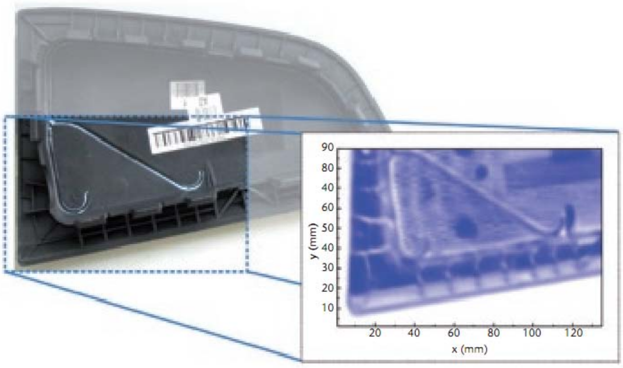

Figure 2.3 : THz imaging of security critical components

A THz image of an airbag cap, obtained in an inexpensive cw THz system, is shown in Figure 2.3. The thickness profile is clearly visualized, demonstrating the ability of cw THz systems for cost efficient quality inspection of polymeric components.[5]

Quality control for food Products

Apart from the polymer industry, another high potential application field for THz systems lies in the food industry quality control. While metallic contaminations (like screws) can easily be detected, non-metallic contaminations (such as stones, plastic parts or glass) seriously challenge conventional measurement systems. Failure in detection is not an option at any rate as it might lead to potentially fatal health risks.[7]

Conventional X-ray systems suffer from the low dielectric contrast between the food product and the contamination. Differentiation between a nut splinter and a sharp glass piece is close to impossible with x-ray devices. Ultra-sonic systems are not contact-free, so that integration in a process line is hard to achieve. Fortunately, THz time domain spectroscopy together with smart data processing algorithms allows for the secure distinction between desired ingredient and unwanted inclusion.

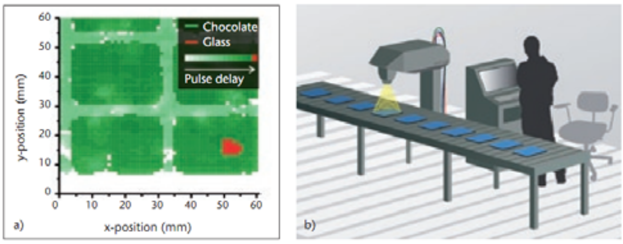

Figure 2.4 : Dielectric inclusions in food products

Figure 2.4 a) shows an image of a nut chocolate with an embedded glass piece. A smart algorithm corrects the error introduced by the uneven surface and the glass piece is clearly visible in the THz scan.[4] Current efforts in developing THz sensor arrays and line scan units will enable the direct integration into the production line as depicted in the schematic drawing in Figure 2.4 b). However, scan speed remains a critical issue for THz imaging applications and further innovations are required before such systems can be introduced into large scale production.

Security Scanning Applications

One of the most receptive fields in regards to THz technology is the security sector. THz systems have unique feature to reveal hidden objects beneath clothing, even if they are of non-metallic nature like ceramic weapons or explosives. Apart from revealing hidden objects, THz systems can also be employed for chemical recognition. Each material has its own spectroscopic fingerprint and the ability of THz systems to access both the refractive index and the absorption information leads to a high accuracy in the detection process.[6] Especially explosives are of interest and within this group foremost the liquid explosives receive much attention, as no other systems exist for their reliable recognition. The vision is a mobile, standoff detection system for check points in conflict areas or a handheld security scanner for the secure identification of liquids at airports.

Figure 2.5: terahertz image of men with hidden knife

Hydrology Monitoring of Plants for optimized irrigation Strategies

The steadily increasing water shortage, induced by desertification and global warming, requires intelligent irrigation strategies, especially for economic plants. The basis for developing such strategies is the understanding of the plant's hydrology.

Here, THz technology might play a key role: Due to the high absorption coefficient and the strong abnormal dispersion of water in this frequency region, the water content of a leaf considerably influences the THz wave propagation.[3] Therefore, THz systems can be employed to investigate this important quantity.

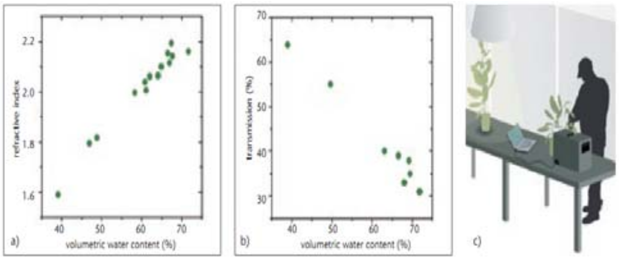

Figure 2.6 : THz technology contributing to the understanding of Plant Hydration

As shown in Fig. 2.6, both the leaf‘s refractive index and its transmission perceptibly depend on the water content. Thus, these measurements can be utilized to observe the water status.[1] The high spatial resolution achievable with THz systems due to the sub-mm wavelengths furthermore enables the potential of investigating the water transport and the water distribution within a leaf by cw or pulsed THz imaging.

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.

Material Characterization

For physics this new technology is very interesting because they can use it for characterization of materials like semiconductors and lightweight molecules.[7] The radiation can be used to determine the carrier concentration and mobility of semiconductors10, and in the superconductor research it can be used to determine the parameters of superconducting materials.

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.

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.[2] A reliable non-invasive probe of burn depth would be of great value to physicians, who currently have no such technology. The detection of skin cancer works very well. 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.

Communication

Potential uses exist in high-altitude telecommunications, above altitudes where water vapour causes signal absorption: aircraft to satellite, or satellite to satellite.

Conclusion

Numerous applications for THz technology exist and many industrial branches can benefit from its unique capabilities. Further improvements in terms of measuring speed, system robustness and cost efficiency have to be implemented to make THz systems even more competitive. Fortunately, a plethora of research projects are currently pursued, so that THz systems rapidly approach large-scale market introduction

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