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Polymer identification with terahertz technology

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Abstract The spectral range of Terahertz-radiation (THz) is currently not fully utilized in industrial applications. The area of secondary raw material (generated waste) characterisation is a field where the technology is currently not applied at all. To transfer the THz-technology towards the raw material sector, the RWTH Aachen and company AMO GmbH cooperate to harness the advantages of THz-technology for material characterization. This paper presents an overview of current fields of application and summarizes the results and projections for an advanced polymer characterization with the help of THz-technology.

1 Introduction or the physics behind "T-rays"

THz-waves or T-rays lie within a relatively unexplored area of the electromagnetic spectrum, which also has been referred to as "terahertz gap" in the past. The waves are located between the infrared and microwave region of the spectrum and therefore lie between optical and electromagnetic ranges, as shown in figure 24.1. The technologies based on "THz" combine electronic and photonic applications. The "gap" is attributed to a lack of efficient sources being able to generate frequencies in the 10^{12} range. Thus the field is, due to its recent emergence, rich in open scientific questions, the technology is yet relatively immature, but rapidly developing [2, p. 1509].

The use of THz-radiation has many advantages. The THz-radiation has no ionizing effect and is not affected by influences due to differences

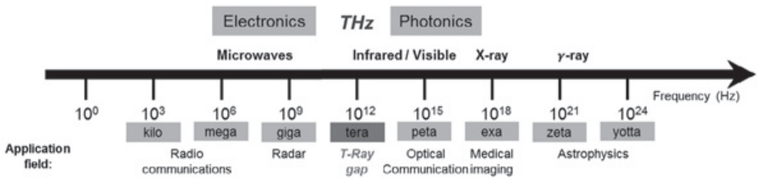

Figure 24.1: Electromagnetic spectrum with "T-ray" gap; based on [1].

in colour; thus dark material can be identified as well as light coloured materials.

One main benefit arising from THz-imaging techniques is the possibility of gathering additional information. During regular image processing or conventional imaging applying visible light, each pixel contains only information on amplitudes, since photo-sensors are only capable of detecting amplitude changes. THz-imaging instead can provide functional images where each pixel contains spectral information. This is typically achieved by terahertz pulsed imaging (TPI) systems that use a pump-probe configuration so that both amplitude and phase information can be gathered [2].

The gathering of imaging or spectroscopic data in the THz range is possible via active or passive methods. The passive measurement uses the T-ray emission at a certain temperature. The active measurement uses the absorption or reflection on objects when exposed to T-rays. The passive method provides information of the thermal properties of objects, their "body" or "internal temperature". This can be mapped as contrast in the imaging data. As an example, the signature of a hot cup of coffee is visible in high intensity, those of a cold metal blade on the other hand appears only at a low intensity [3].

2 Area of application

The generation and detection of THz-radiation is still cost-intense, therefore it is only applied in certain industries. Current applications are, for example, quality control of high-priced products in the food and medicine sector. Many materials are hereby identified by a fingerprint-method based on a characteristic absorption patterns in the terahertz range.

The most common application for THz-technology lies in safety or security applications. The so-called "full-body scanners" used for passenger controlling at airports work at the lower THz range [4]. THz imaging and spectroscopy works contact-free and without use of ionizing radiation [5, p. 71]. With this surveillance device it is possible to detect hidden weapons or explosives at a high reliability without manual frisking of passengers [3]. In order to examine an object in the THz range, to be able to generate imaging or spectroscopy data, either passive THz-radiation, emitted at a certain temperature or active radiation irradiated by THz sources is detected. Full-body scanners apply as well active as passive THz-radiation. During passive sensing methods the differences in thermal imaging of objects due to their internal temperature provides a visible contrast. For the scanned passenger a passive sensing means that the contour of the body is not visible as a sharp image and therefore the resulting image is more polite and accepted by individual persons [3, p. 296].

3 Transferring THz towards raw materials

The raw materials industry increasingly faces new challenges, like growing industrial nations, improved living standard and up-keeping economic power, to provide a secured and sufficient raw material-supply. The growing demand for raw materials leads to the necessity of satisfying the demand for primary raw materials as well as for high-quality and pure secondary raw materials from waste streams by recycling processes. This demand can only be reached by advanced processing and sorting technologies. As the following example shows:

There are many materials which cannot or only with difficulties be identified with established sensor-based sorting techniques. One example are dark-coloured materials, especially dark or black-coloured polymers. Due to the lack of sufficient reflection in the visible spectrum detection with, for example, Near-Infrared sensing for the detection of dark polymers is not possible. The THz-technology holds the potential to achieve a technical solution for this yet unsolved problem. Furthermore it might not only allow the determination of the type of polymers, but also the identification of used additives. The detection might prevent further downcycling in closed-loop recycling processes. One central question resulting here from is whether, measurement methods based on THz-technology can be applied for distinguishing different polymer types and their additives.

4 Test measurements

To reveal the many advantages of THz technology for the raw material sector, researchers of the RWTH Aachen research group 'SiR' (Sensor Technology in the raw materials industry) initiated a project with AMO GmbH.

The aim of this research cooperation is to evolve a THz-sensing system for raw material identification, especially polymer identification. At the time there is no information available on the applicability of this technology in the raw material industry. The first lab measurements conducted by AMO GmbH and the SiR-group clearly show the potential and possibilities for this new field of application.

The test measurements have been conducted in terms of proof-of-principle for the implementation of THz-technology into the raw material industry. The main focus of the first measurements has been set on the identification of different coloured polymer types - some of them being subject of the mentioned lack of sorting technologies. The measurements were carried out at the local AMO GmbH which is specialized in the development of custom-designed sensor heads and near-field probes for the THz-range.

A waveguide-based probing configuration depicted in Fig. 24.2 and developed by AMO has been applied for this study. The set-up is based on a classic optical pump/probe scheme which is widely used for THz time-domain spectroscopy [6]. A pulsed laser system with a centre wavelength of 810 nm, 150 fs pulse duration and a pulse repetition rate of 78 MHz is used as the optical signal source. The laser beam is split into a pump and a probe beam. For THz generation the pump beam is focussed on a photoconductive THz emitter structure which is held in direct contact with a THz slit-waveguide (SWG) [7] with a length of 76 mm. This type of waveguide is characterized by low attenuation and very low dispersion and the lowest-order propagating field mode, illustrated in Fig. 24.2 (a), is well confined to the slit region. The main

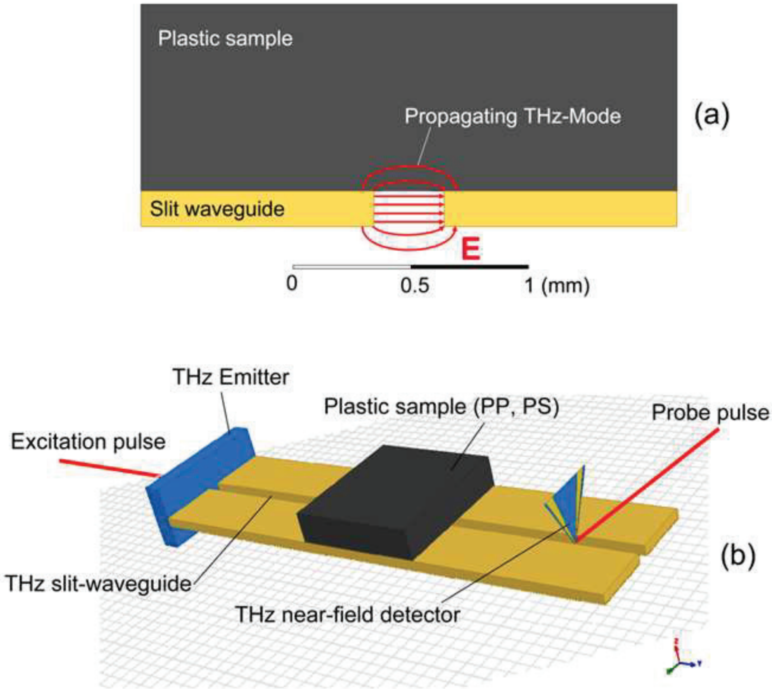

Figure 24.2: (a) Cross-section view of the THz slit-waveguide with sample material and the field distribution of the main propagation mode. (b) Schematic illustration of the applied measurement configuration.

function of the SWG is to control and enhance the THz field interaction to the sample structures placed on it. The waveguide slit has a width of 300 μm and a height of 150 μm. Each optical excitation pulse at the emitter generates a THz pulse which is propagating along the SWG. A photo-conductive near-field (NF) probe-tip [8] is placed in the slit in a longitudinal distance of 10 mm from the open end of the waveguide. The NF probe contains an ultra-fast photoswitch which is "opened" for a very short duration (approx. $200 fs$) every time a probe pulse impinges. The time delay **t** between the emitter and the probe pulse is controlled by an opto-mechanical delay stage. In this way the THz pulse propagating along the SWG can be sampled in the time-domain and the average photocurrent $\mathbf{I}_{pc}(t)$ measured at the NF probe is proportional to the adjacent THz field amplitude $\mathbf{E}_{THz}(t)$. As shown in Fig. 24.2 (a) and (b), the sample under test is placed on the SWG between the emitter and the detector. Hence, a part of the transmitted THz field is penetrating a part of the sample volume which in return (depending on its dielectric properties) is causing a material specific modification of the transmitted signal [9].

The considered sample materials consist of the polymer types: polypropylene (PP) and polystyrene (PS). Both polymer types are provided in two different colours, so that estimations can be made whether different colours show characteristic differences in the detected signals. The samples are analysed regarding their different THz-transmission properties. In order to ensure a direct relation of transmission changes to differences in dielectric sample properties in this simple first configuration all samples were cut in to comparable sized pieces of ca. $17\ mm\ x\ 10\ mm\ x\ 2-3\ mm$ length. Samples were measured along the length directions of $10\ mm$ (in the following denoted by index 1) and $17\ mm$ (index 2) lying flat.

The results of the measurements are summarized in the following figures (Figs. 24.3 and 24.4). In both figures the blue line determines the reference value, the THz-pulse without sample. Figure 24.3 shows the results for the measurements with polystyrene (PS) samples (PS black 1/2, PS clear 1/2). The second figure displays the results of measurements with polypropylene samples (PP black 1/2, PP grey 1/2) [9].

5 Results

At first view, the time evolution of the transmitted signals appears to be relatively complex which is caused by an instantaneous generation of three modes at the sample forefront. Each mode has a different sample interaction behaviour and propagation speed. The modes are clearly separable by comparison of the different propagation lengths. The transmission signals proved to be very robust against slight sample displacements and rotations. Characteristic differences in the transmission properties of the two polymer types PP and PS are clearly visible

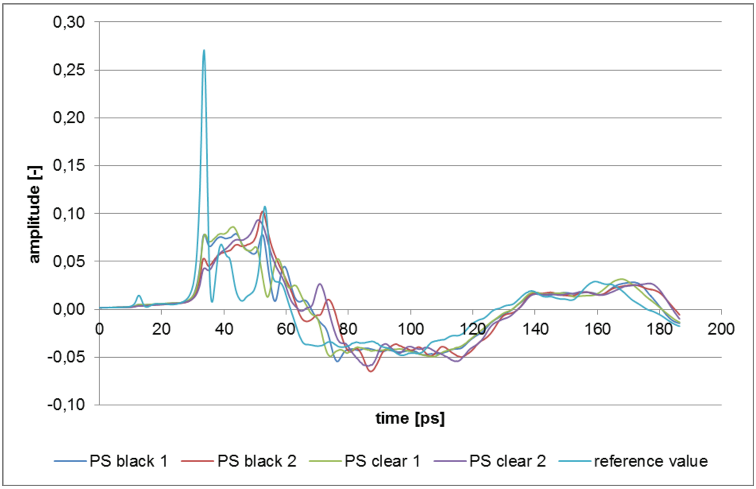

Figure 24.3: Measurement of different PS samples, source: [10]. *With friendly permission of AMO GmbH.*

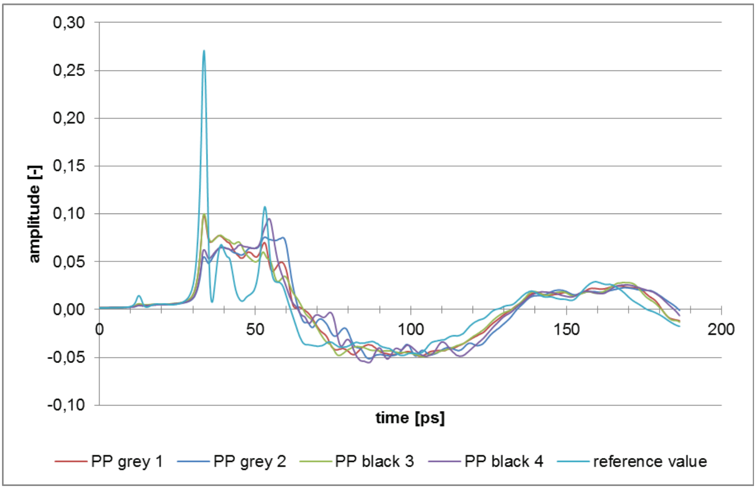

Figure 24.4: Measurement of different PP samples, source: [10]. *With friendly permission of AMO GmbH.*

from the data. Significant transmission differences are also observed for the different colour grades of each polymer type. The results reveal that the PS samples can be clearly distinguished from PP because of a lower refraction index in the THz range [9].

In conclusion, we have shown that there is a possibility of identifying critical types of polymers with THz probing technology. The application of this approach to arbitrarily shaped samples will require a measurement of the size of the sample or a design modification of the waveguide structure with suppressed sensitivity to this parameter. Detection of sample sizes could be achieved by implementing a 3D measurement system using laser triangulation techniques prior to the THz measurement.

The results show that application of THz probing in the raw material industry is very promising and surely worth further research. The topic of material recognition, especially recognition of dark materials (e.g. from shredded cars), is still an unsolved problem. Terahertz technology might become an important part of the technical solution in the nearby future.

6 Summary and outlook

But, even if the results show a high potential some restraints have to be taken into consideration. In the waste sector every technology underlies the "human factor": every detected material underlies a certain anthropogenic influence. So it is urgent, that this influences in materials have to be erased by a high number of measured objects. Therefore to evolve the THz-technology into the waste sector, large amounts of single objects have to be measured to generate a data base for further statistical analysis. At the moment measurements are still too time and cost intense to generate the required amount of data, due to the lack of cheap and sufficiently powerful THz-devices. But the already visible high potential for the raw material industry is a very strong argument to start dealing with Terahertz-technology.

At the moment there is no deeper knowledge available on the applicability of this technology into the raw material industry. The first lab measurements clearly show potential for further research and applicability for raw materials. But it is urgently required to increase the effort in research and development for implementing this technology into the raw material sector.

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