Terahertz imaging: applications and perspectives

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Terahertz (THz) spectroscopy, and especially THz imaging, holds large potential in the field of non-destructive, contact-free testing. The ongoing advances in the development of THz systems, as well as the appearance of the first related commercial products, indicate that large-scale market introduction of THz systems is rapidly approaching. We review selected industrial applications for THz systems, comprising inline monitoring of compounding processes, plastic weld joint inspection, birefringence analysis of fiber-reinforced components, water distribution monitoring in polymers and plants, as well as quality inspection of food products employing both continuous wave and pulsed THz systems. © 2010 Optical Society of America

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1. Introduction

Located between microwaves and the infrared, the terahertz (THz) region remained a nearly untapped part of the spectroscopic portfolio for a long time, as neither electronic nor optical sources could illuminate this shadowy region. The advent of femtosecond (fs) lasers paved the way for numerous pulsed THz emission and detection schemes [1–6]. Furthermore, continuous wave (cw) THz systems, e.g., those based on photomixing two diode laser beams, were developed in the mid-1990s. Besides these optical approaches to THz generation, electronic devices, e.g., the Gunn oscillator-driven Schottky multiplier chains, also advanced in this field [7–11], enabling low-cost system architectures.

A plethora of applications for THz systems has been introduced in the literature [12], ranging from biological imaging, nondestructive testing (NDT), security scanning, and process control to next-generation wireless communication systems [13,14]. The enormous inherent potential of THz technology led to a rapid development of THz systems, and, today, the first commercial products are available. While measurement speeds still require improvement and system costs are relatively high, THz systems are on the brink of large-scale market introduction.

The remainder of the paper is structured as follows: First, we will discuss a representative example of both a pulsed (Subsection 2.A) and a cw THz system (Subsection 2.B) followed by a review of selected industrial applications for THz systems (Section 3), especially focusing on the prospects of THz imaging. Among the investigated subjects are the identification of the glass transition temperature of semicrystalline polymers, inline monitoring of compounding processes, plastic weld joint inspection, birefringence analysis of fiber-reinforced components,
water distribution monitoring in polymers and plants, as well as the safety-critical quality inspection of food products. Our conclusions are presented in Section 4.

2. Terahertz Spectroscopy Systems

Among the many realizations of THz systems, two basic principles can be differentiated: either electromagnetic picosecond pulses, which have spectral components ranging from approximately 100 GHz to several THz, are generated, or cw radiation is employed. While the former method offers the advantage of broad spectral information from a single scan, cw techniques are the first choice when sharp spectral features are of interest and a frequency resolution down to a few MHz is desired [15].

Pulsed THz systems have recently overcome a major drawback, namely, high system costs, as the advent of Er³⁺-doped fs fiber lasers has brought an inexpensive replacement for titanium:sapphire sources. Furthermore, the emission wavelength of such fiber lasers is 1550 nm, so that standard telecom components can be employed. Unfortunately, GaAs-based photoconductive antennas (PCAs), which are frequently employed as emitters and detectors in 800 nm systems (also see Subsection 2.A), are transparent to the 1550 nm wavelength. Therefore, an alternative substrate material had to be found. This obstacle was overcome by the introduction of 1550 nm compatible semiconductor materials (e.g., Fe-implanted InGaAs or InGaAs/InAlAs quantum film stacks on InP wafers) [16,17]. The Er³⁺-doped fiber lasers, the 1550 nm telecom components, and the new compatible PCAs have led to the development of less expensive, robust, all-fiber THz systems that are attractive for many industrial applications [18]. In the following two sections, we briefly discuss the basic principle of both pulsed and cw THz generation and detection. For a more complete overview of THz sources and detectors, the interested reader is referred to the excellent reviews published elsewhere [1,3,19–21].

A. Broadband Pulsed Terahertz Systems

Optical gating of PCAs is one of the most popular THz generation and detection schemes [22–24]. As illustrated in the upper part of Fig. 1(a), a fs laser source (e.g., a titanium:sapphire laser or Er³⁺-doped fiber laser) emits ultrashort, sub-100 fs pulses, which are split into an emitter and a detector arm. In the emitter arm, the optical pulse is focused onto a biased PCA. The optically excited electron hole pairs are accelerated in the externally applied field, which induces the emission of a THz pulse with spectral components exceeding 3 THz. The THz pulse is guided by polymeric lenses or by off-axis parabolic mirrors and is finally focused onto the detector PCA. Here, the inverse principle of the generation process is employed for the detection of the THz pulse: again, the optical pulse gates the photoconductive detector by generating free carriers. Instead of applying an external field, the incoming THz field accelerates the carriers and drives them into the electrodes. The temporal length of the optical gating pulse is of the order of tens of fs, while the THz pulse is of the order of picoseconds. Thus, the resulting photocurrent, which is detected by a low-noise multi-stage transimpedance amplifier, corresponds to a single point of the THz pulse shape. By introducing a varying time delay in one of the arms, which can be either a mechanical delay line or, for video rate applications, a fiber stretcher, the complete THz pulse can be sampled step by step.

It is worth mentioning that such a generation and detection scheme enables the monitoring of highly dynamic processes, as it offers a typical signal-to-noise ratio of up to 70 dB. Furthermore, due to the coherent nature of this technique, both phase and amplitude information are available. Measuring a first pulse without a sample in the THz beam path and a second pulse with the sample present allows for the simultaneous extraction of the refractive index, the absorption coefficient, and the thickness of the sample, providing detailed information about the sample under investigation [25].

In Fig. 1(b), a photograph of a fiber-coupled THz time domain spectroscopy (TDS) system is depicted. The metallic enclosure contains a free space fs laser system with chirp precompensation for the attached glass fibers and a delay line. The fiber-coupled outputs are connected with polarization maintaining fibers to the emitter and the receiver measuring heads. Later, we will discuss inline measurements that were performed using such a rugged, mobile industrial THz TDS system.

B. Continuous Wave Systems

If spectral resolution is the primary concern, e.g., to study sharp absorption lines of gases, cw THz systems deliver outstanding performance. In contrast to pulsed THz systems, no fs lasers are required. As shown in the lower section of Fig. 1(a), the output of two frequency stabilized laser diodes is spatially overlapped in a beam combiner and focused onto a PCA with an optimized electrode geometry [26]. Instead of the ultrafast carrier dynamics employed in the pulsed case, mixing of the two incident waves is exploited to generate a continuous THz wave, which oscillates with the difference frequency of the two incoming waves [27–29]. By detuning one of the laser diodes, the emission frequency can be swept in a wide spectral range. A second PCA is employed for coherent sampling of the incoming THz radiation [30]. Even though pulsed systems are decreasing in price, cw systems are still less expensive and feature a frequency resolution down to 2 MHz.

C. Approaches Toward Fast Terahertz Imaging

Many applications in NDT require imaging techniques. Methods such as x-ray or ultrasonic testing employing detector arrays generate images in or close to real time. Conventional THz TDS systems,
as described above, are designed to generate highly precise spectroscopic information at a single point of a sample. Thus, to generate full images at high speeds, several considerations have to be taken into account.

Among the concepts for terahertz imaging, several noncoherent techniques, including microbolometer arrays [31], have been presented. While increasing the measurement speeds, these approaches give only limited information due to the lack of phase information.

The most basic coherent imaging can be achieved by raster scanning a sample through the THz focus and generating full spectroscopic information at each pixel. Considering a small image of 60 by 60 pixels, 3600 single measurements are required. Depending on the delay line concept, the desired lock-in time constants, and other factors, to record a high-quality THz pulse can take longer than 30 s and can result in a total measurement time of 30 h for a full image. This example shows the necessity of parallel or accelerated measurements.

A straightforward approach to parallelization is a multiantenna setup enabling a linear downscaling of the measurement time with the number of employed emitter and detector pairs. However, arrays have to be developed to counter the drastically increasing costs, e.g., as demonstrated in [32]. Even though multipixel approaches yield a clear acceleration of THz measurements and could lead to attractive system architectures in the future, severe problems in the alignment process are still major drawbacks that must be overcome. So far a maximum of 16 parallel channels has been experimentally demonstrated [33].

A parallel approach to coherent two-dimensional electro-optic imaging is presented in [34]. These systems use a ZnTe crystal to convert a THz signal into a two-dimensional optical image, which can be recorded by a CCD camera. Recently, real-time measurement speeds have been achieved [35]. However, the required laser power scales linearly with the number of pixels, limiting the applicability of systems such as expensive laser systems with an output power of several hundred milliwatts to be employed.

Compressed sensing is an approach to generate THz images without time-consumingly moving the sample or detector [36]. The sample is illuminated by a collimated THz beam, together with a known random pattern of opaque pixels. When changing the pixel pattern often enough, an image of the sample can be reconstructed, for example, where 300 different patterns result in a resolution of 1024 pixels.

Alternatively, conventional single-pixel imaging systems can be used if steps toward a shorter single point scan time are taken. Especially, new delay line concepts can drastically shorten the required pulse acquisition time. Conventional delay lines are based on mechanical linear stages with a retro-reflector mounted on top. Moving these delay lines with a high precision leads to relatively slow scan rates. An alternative concept uses fiber stretchers, which create a delay by elastically stretching a glass fiber, inducing a relative change in the fiber length of less than 1%. Combined with interferometric length measurements, this device can precisely scan THz...
pulses with several Hz, so that, if no further averaging is applied, the 3600 pixel image mentioned above can be acquired in less than 10 min—orders of magnitude faster than with a conventional system. Furthermore, these devices neatly integrate in rugged all-fiber setups. In the future, improvements in this field could lead to fiber stretchers with kilohertz acquisition rates, enabling real-time THz imaging.

Visualization techniques for coherent THz image information include peak-to-peak measurement, time-of-flight measurement, amplitude measurement at single frequencies, integrated signal amplitude over a specified frequency range [37], and evaluation of the dielectric material properties [refractive index \( n \) and absorption coefficient \( \alpha \); see Figs. 2(a) and 2(b)]. Thus, multiple images revealing different kinds of information can be created from a single data set, e.g., variations in thickness, density, material composition, or humidity, as well as inclusions of air or other foreign bodies in the sample [see Figs. 3(a) and 3(b)].

3. Industrial Applications for Terahertz Systems

In the previous sections we discussed the basics of THz generation and detection as well as approaches to THz imaging. Now we shall investigate industrial applications for THz systems, focusing on imaging but also considering some single point measurement scenarios. The illuminated scenarios comprise examples from the polymer processing industry, the food industry, and plant breeding. Because of the manifold activities in this field and the limited length of this article, we can only discuss a small excerpt of the emerging THz applications and refer the interested reader to other excellent reviews for additional information [20–21, 38–40].

A. Terahertz Spectroscopy of Polymers

In past decades, the production volume of plastics has overhauled that of steel and is continually increasing. To refine production techniques and open new markets for plastics, the polymer processing industry is continuously investigating new process control and NDT techniques, as many challenging measurement tasks of the production lines remain unanswered.

Polymers and THz waves form a fruitful symbiosis, as many plastic materials are transparent to THz radiation and serve as a base material for passive THz system components [41–43]. In return, THz systems can reveal valuable information of the composition of polymers and the inner structure of polymeric components. In the next three sections, we will successively discuss applications of THz technology throughout the value creation chain, starting with offline measurements for the characterization of molecular properties, considering the following inline process monitoring with real-time feedback, and referring finally to quality inspection of the polymeric components.

B. Polymer Characterization on a Molecular Level

To fully understand the potential of THz sensors for polymer testing applications, a closer look at the underlying physics is mandatory. The most prominent interactions between THz waves and polymers are collective motions of large molecules, which appear as broad absorption bands. Some far-infrared absorption spectroscopy studies have already investigated skeletal vibrations, liquid lattice modes, hydrogen bonds, and intermolecular vibrations in the crystalline phase [44]. However, THz TDS systems have a clear advantage here, as the simultaneous extraction of the refractive index, the absorption coefficient, and the sample thickness [25] offer information that complements and exceeds the far-infrared absorption data.

Exemplarily, we will discuss the contribution that THz TDS can provide to the identification of the glass transition temperature. Glass transition in amorphous or semicrystalline polymers often limits their operating temperature range. Elastomers, for example, become brittle below the glass transition temperature \( T_g \), as segmented chain motion is frozen.
Conventional methods for determining $T_g$ are differential scanning calorimetry (DSC) \cite{45} or dynamic mechanical analysis \cite{46}. However, as the glass transition is restricted to the amorphous domains of a polymer, the conventional methods can fail when a high crystallinity is present. Thus, a number of polymers exist in which the glass transition temperature is not clearly identified.

Scientifically speaking, the glass transition is not a classical thermodynamic phase transition but, rather, a relaxation process that can be understood by the concept of the free volume \cite{47}. In this model, the unoccupied space between the macromolecules is referred to as the free volume $V_f$. Beneath $T_g$, the free volume does not change with the temperature. However, above $T_g$, a linear increase of $V_f$ is observed [see Fig. 4(a)].

In \cite{48}, the authors demonstrated that the temperature-dependent THz refractive index can reveal even minute changes in the free volume, which is related to the specific volume and the density of the sample. Thus, THz TDS is able to indicate the glass transition temperature with high precision and also in the case of highly crystalline polymers, where other techniques have failed so far. In Fig. 4(b), we show the temperature-dependent refractive index of poly(oxymethylene) (POM) at 1.5 THz. The gradient of the refractive index changes at the glass transition identified as $T_g = 199$ K. Above $T_g$, the free volume starts to increase inducing a change in the density, which directly correlates with the refractive properties of the sample. In comparison, we also show the glass transition temperature range identified by DSC measurements (gray area), which is in perfect agreement with the THz TDS results. Hence, we conclude that THz TDS can reveal the glass transition temperature of polymers.

C. Terahertz Systems for Inline Process Control

The majority of technical plastics consist of a base polymer compounded with additives that enhance its functionality and allow for the design of a custom-tailored product. Commonly employed additives include flame retardants, colorants, and low-cost filling materials. Inline or online monitoring of the additive concentration inside the polymeric melt is a challenging task. Recently, we demonstrated that rugged THz TDS systems (as shown in Fig. 1) can give valuable information about the compounding process \cite{49–51}. Figure 5(a) shows inline measurements on polypropylene with a varying content of CaCO$_3$ performed at the end of an extruder [Fig. 5(b)].

![Fig. 3. (Color online) Images of drilled holes in a plastic sample: (a) photography, (b) peak-to-peak THz-image, and (c) integrated intensity in the range of 0.2 to 0.3 THz.](image)

![Fig. 4. (Color online) (a) Volume-temperature diagram of a polymer and (b) temperature-dependent refractive index of POM at 1.5 THz observed with THz time-domain spectroscopy [the gray area in (b) denotes the glass transition temperature range identified by DSC measurements].](image)
dashed curve indicates the to-be weight percentage of CaCO$_3$ in the melt determined by the dosing units at the extruder input on the basis of gravimetric measurements. The solid curve corresponds to THz amplitude data measured at the extruder outlet. To increase the THz TDS measuring speed, the THz amplitude is determined only at a single point of the delay line. When the concentration of the additive changes, the THz pulse shifts, which induces a sensitive response in the detected THz amplitude at the fixed time delay. The THz data (dashed curve) clearly reveal the residence and washout time of the additive inside the extruder. For a detailed discussion of these initial THz inline measurements, the interested reader is referred to Ref. [49].

D. Quality Inspection of Plastic Components

Besides basic material characterization and process monitoring, THz systems could play a major role as instruments for the nondestructive, contact-free inspection of plastic components. THz imaging can determine, for example, the spatially resolved fiber orientation in reinforced polymers or reveal delamination and inclusions in plastic weld joints.

E. Fiber Orientation in Reinforced Plastic Components

An increasing number of components, especially in the automotive and aircraft sectors, consist of fiber-reinforced materials, which offer high mechanical strength at low component weight. Especially, safety-critical parts should pass a contact-free, nondestructive 100% testing procedure to ensure correct operation. Conventional techniques still struggle to fulfill this demand, so that THz technology could provide a valuable contribution to this field as demonstrated in [52,53].

The preferential orientation of fibers and fibrils inside a polymeric host medium induces a birefringent dielectric behavior at THz frequencies [54,55]. Generally speaking, the refractive indices $n_{oa}$ and $n_{ea}$ of the ordinary and the extraordinary axes of a birefringent medium span an ellipsoid [Fig. 6(a)]. By determining the THz refractive index of the composite at three different angles between the THz polarization and the sample, this index ellipsoid can be reconstructed, revealing the preferential orientation direction as well as the overall orientation degree of the fibers at a single spatial position of the plastic component.

In Fig. 6(b), we show the simulated fiber orientation tensor (false shaded image) according to Moldflow Plastic Insight software of an injection molded polyamide reinforced by 30 wt.% short glass fibers. The black arrows mark the average fiber orientation determined by the THz measurements at the corresponding points, applying the index ellipsoid model to the refractive index data at 0.6 THz. The length of the arrow corresponds to the fraction of preferentially oriented fibers due to the magnitude of the

Fig. 5. (Color online) (a) Inline terahertz measurements on polypropylene melt with a varying content of CaCO$_3$ performed at the end of an extruder and (b) compact THz probe for inline process control.

Fig. 6. (Color online) (a) Index ellipsoid of a birefringent medium and (b) simulated fiber orientation tensor (false shaded image) according to the software Moldflow Plastic Insight of an injection molded polyamide specimen reinforced by 30 wt.% short glass fibers.
birefringence. Comparing both the simulations and measurements reveals deviations of the preferential orientation from the mold flow direction, which can be explained by deflection at the borders of the specimen, the potential influence of a middle layer, and the presence of dwell pressure during the injection molding process. For further information on this innovative application of THz technology, we refer the reader to Ref. [56].

F. Quality Inspection of Plastic Weld Joints

Plastic components are commonly employed as construction materials, replacing more expensive materials, such as metals or ceramics. Hence considerable interest is also drawn to related joining technologies, such as plastic welding, which enables this constant progress. For example, nearly all the newly constructed pipelines for gas transportation are made of polyethylene. Hence, the quality of weld joints is of paramount importance, as their structural integrity might be severely affected by contaminations, air bubbles or delamination. Unfortunately, x rays and ultrasonic waves are not able to satisfactorily identify such defects. Today, due to the lack of a proper NDT technology, only the parameters of the welding process are monitored at the risk that the joint might fail—in consequence, possibly inflicting considerable damage.

In [57], we demonstrated that THz imaging could improve this unsatisfying condition. As proof of this principle, we investigated welded high-density polyethylene samples with dielectric sand contaminations and with a delamination. Backlit photographs and corresponding THz images of the contaminated and delaminated sample are shown in Figs. 7(a) and 7(b), respectively. Both the sand inclusions and the delaminations are clearly resolved. Figure 7(c) shows a future application scenario of a THz NDT plastic weld joint inspection system.

G. Determination of Water Content in Plastics

The physical and mechanical properties of a polymer are severely influenced by its water content [58,59]. THz waves are strongly absorbed even by minute amounts of water, so that changes in water concentration can be reliably detected. Hence, THz sensing has an inherent potential in this field. For instance, we demonstrated that the water content in hygroscopic polymers and compounds such as polyamide and wood plastic composite (WPC) can be accurately determined [60]. Furthermore, an effective medium theory-based model of the dielectric material characteristics independent of the water content has been introduced. Figures 8(a) and 8(b) show a photograph and a THz-image of the water content inside a WPC plate (60 wt. % wood fibers). Higher water contents result in a stronger attenuation of the transmitted THz pulse. The sample was immersed in distilled water from the right-hand side. As expected, we find the highest concentration with approximately 2.5 vol. % of water at the right sample edge. To the left, a gradual transition from higher to lower water concentrations is revealed by an increase in the THz transmission. For more details, the reader is referred to [58].

H. Hydration Monitoring for Optimized Plant Breeding

In recent years, water efficient irrigation strategies for economic plants have gained importance to counteract desertification and water shortages. A central question in the optimization of irrigation schemes is...
the in situ identification of drought stress in plants. Because of the high sensitivity of THz radiation to water, even low water contents inside a leaf are reliably detectable. To demonstrate these capabilities, Fig. 9(a) shows a THz image of a leaf obtained in a cw system using a confocal configuration [61]. Darker areas in the picture indicate a higher water concentration in the leaf, revealing the leaf veins. Figure 9(b) shows the THz transmission through a single point of the leaf as a function of the volumetric water content. Based on these findings, plant physiological studies of the hydration state of leaves, and the underlying water transport mechanisms inside the plant appear as another innovative prospect for THz technology [62]. Figure 9(c) depicts our vision for a future mobile hydration monitoring THz TDS system for optimized plant breeding, which is currently subject to active research.

I. Quality Inspection of Food Products

Aside from the discussed applications in the polymer processing industry and plant hydration monitoring, THz imaging systems might also find their way into the quality control of food products. While state-of-the-art quality control systems can easily detect metallic contaminations, nonmetallic contaminations are often hard to find. Existing approaches, such as ultrasonic or x-ray scans, fail when the density difference or the dielectric contrast between the material and the contamination is low. These methods, for example, cannot reliably detect stones, plastic pieces, or glass splinters inside chocolate, even though such contaminations could impose serious health risks for consumers. As THz scans consider not only the absorption spectrum but also the phase information due to the underlying coherent emission and detection scheme, many parameters can be employed for the identification of undesired inclusions. Figure 10(a) shows a THz scan of a chocolate bar that is contaminated by a buried glass splinter. The THz image based on the phase delay clearly reveals the presence of the contamination. In the same manner, we have demonstrated the detection of plastic inclusions and small stones. THz TDS can even differentiate between intended ingredients, such as nuts, and dangerous contaminations, so that it holds the potential to become an established method in the quality inspection of food products [Fig. 10(b)]. However, before that vision can become reality, the imaging speed has to be increased, so that close to real time images can be obtained.

4. Conclusion and Outlook

Many applications, ranging from nondestructive process monitoring and component testing in the polymer industry to quality inspection of food products and even optimized plant breeding, can benefit from the valuable insight THz imaging systems offer. To live up to its enormous inherent potential, THz technology has to become fast and affordable, which requires new approaches to many details of the THz system architecture. A first step has been made in [63] where a compact quasi-THz TDS system without the need for a femtosecond laser source was introduced, enabling mobile and cost-effective system designs in the near future. Such research progress encourages the vision that in less than a decade from now, THz systems will have made the move out of laboratories to real-world applications.

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**Fig. 9.** (Color online) (a) THz image of a leaf obtained in a cw system with a confocal configuration, (b) THz transmission through a single point of the leaf as a function of the volumetric water content, and (c) a future vision of a mobile plant hydration monitoring THz TDS system.

**Fig. 10.** (Color online) (a) THz image of a chocolate bar contaminated with a buried glass splinter and (b) vision of a future THz quality inspection system for food products [21].
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